Effect of Mechanical Stress on GaN HEMT Channel Resistance and Gate Current

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MURI Review Meeting
May 24, 2010

GATOR Engineering
UNIVERSITY OF FLORIDA

Outline

- Motivation
- Effect of Stress on GaN HEMT Channel Resistance
- Experiments on Stress Dependence of GaN HEMT Gate Leakage
- Theoretical Study of GaN HEMT Gate Leakage
- Summary
- Path Forward

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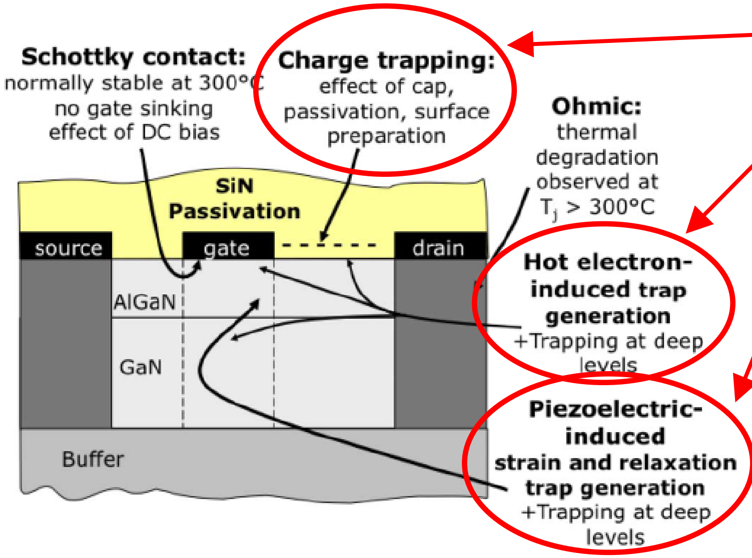
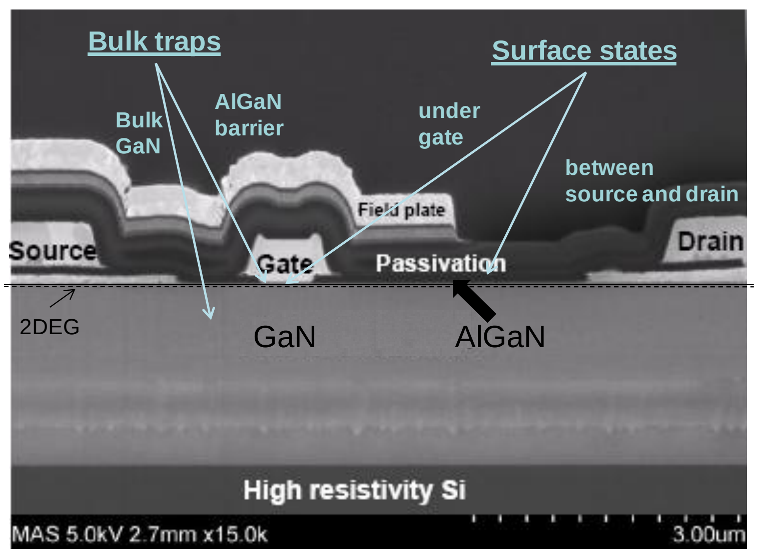
Failure Mechanisms and Traps in GaN HEMTs



Influenced by stress

- carrier mobility
- polarization and 2DEG
- Schottky barrier height
- bandgap
- trap energy levels
- generation of traps

G. Meneghesso, *et al*., IEEE Trans on Device and Materials Reliability, Vol. 8, 2, 2008

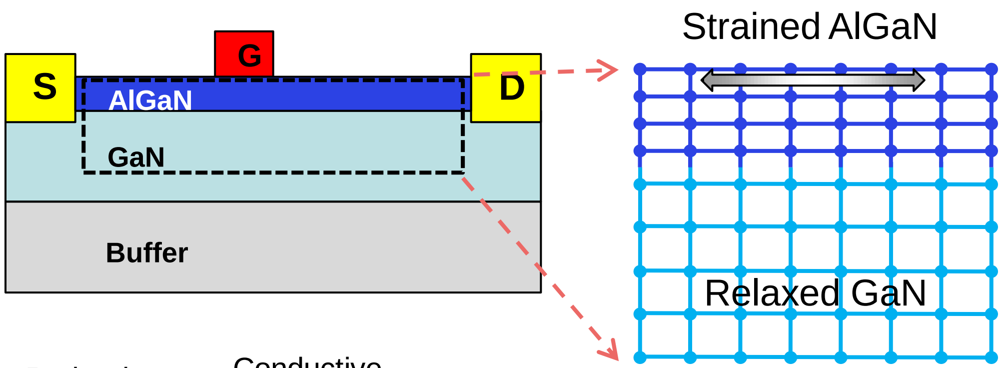


Traps in GaN HEMTs

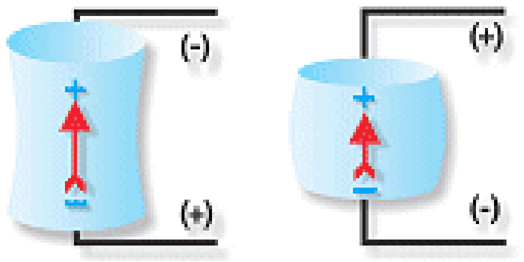
Cause	Effect
• growth *as fabricated* traps • post growth process *as fabricated* traps • hot-carrier injection *generated* traps • inverse piezoelectric strain *generated* traps	• current collapse • gate-lag • drain-lag • ΔV_T • increased I_G • light sensitivity • breakdown

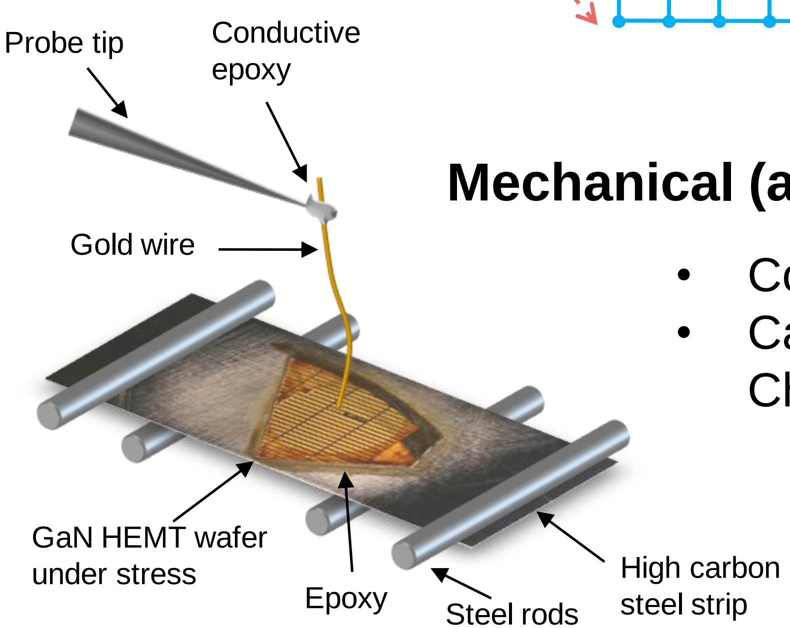
Stress in GaN HEMT Devices

Lattice mismatch (built-in) stress:



Inverse piezoelectric (generated) stress:





Mechanical (applied) Stress

- Cost effective method to study stress effects
- Can incrementally apply and release stress while Characterizing electrical response

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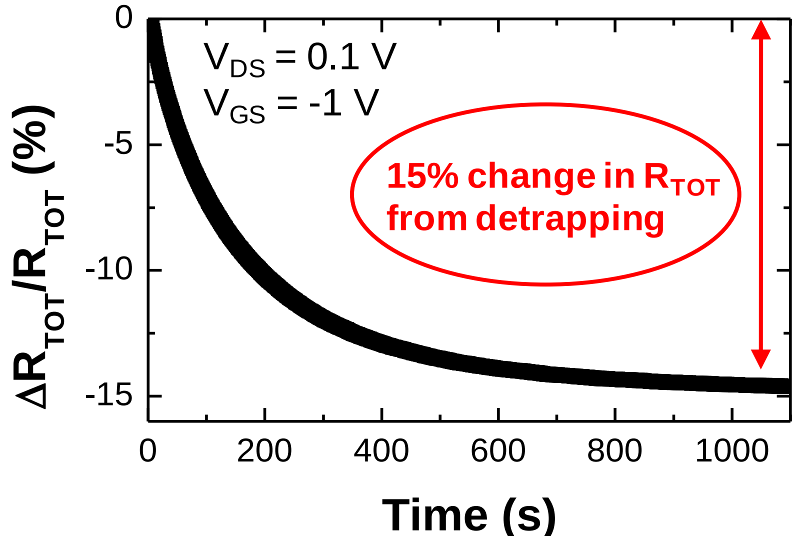
Wide Range of Published GaN HEMT GFs

Ref.	GF	ΔR/R	σ (MPa)	Method of Stressing
[1]	-4	0.14%	95	3-point bending
[2]	-42	0.2%	15	3-point bending
[3]	-75	3.5%	126	3-point bending
[4]	-90	15%	525	Cantilever
[5]	-350	5%	45	Lever-Mass
[6]	-1,259	1.7%	0.42	Cantilever
[7]	-38,889	15%	1.2	Circular Membrane

Microscope light ON

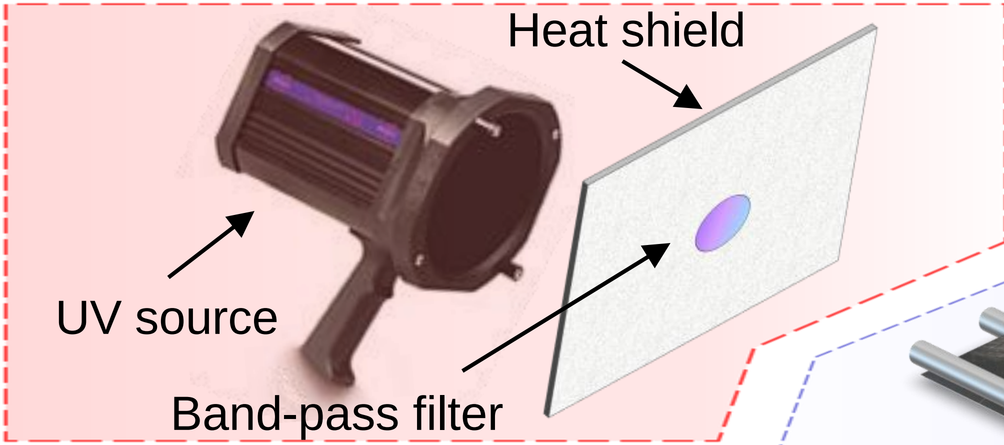
(Commercial Sample)

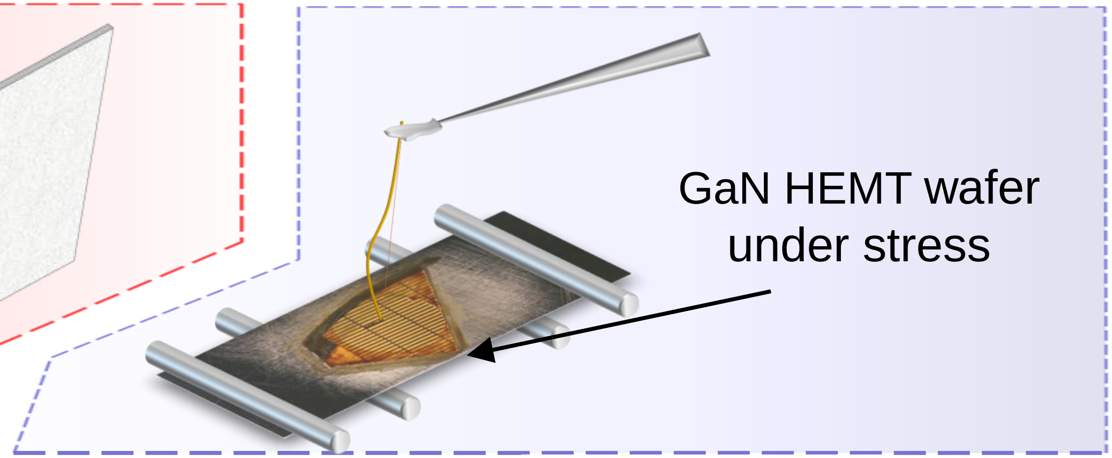


Largest change in resistance measured is ~15%
Could result from charge trapping effects

[1] R. Gaska, et al, *APL*vol. 72, 1998.
[2] M. Eickhoff, et al, JAP, vol. 90, 2001.
[3] C. T. Chang, et al, *IEEE Electron Device Letters,* vol. 30, 2009.
[4] T. Zimmermann, et al, *IEE Electron Device Letters, vol* 27,2006.
[5] O. Yilmazoglu, K. et al, *EICE Trans Electron,* vol. E89-C, 2006
[6] B. S. Kang, et al, *APL,* vol. 83, 2003.
[7] B. S. Kang, et al, APL, vol. 85, 2004.

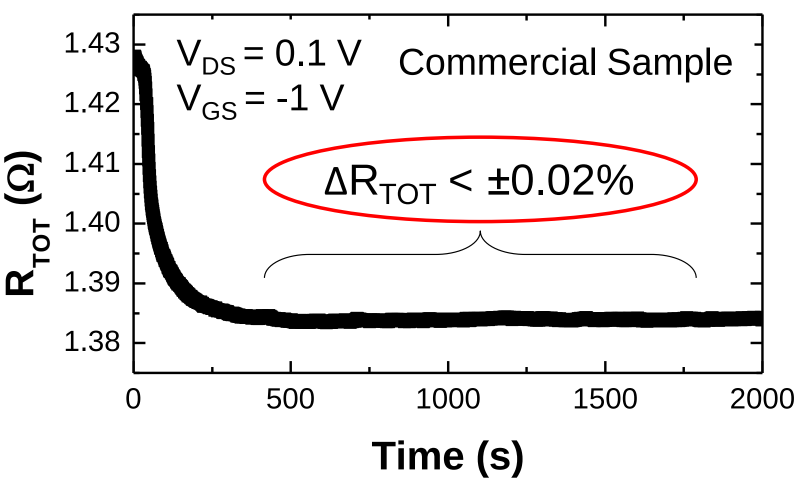
Measurement Procedure – UV Illumination



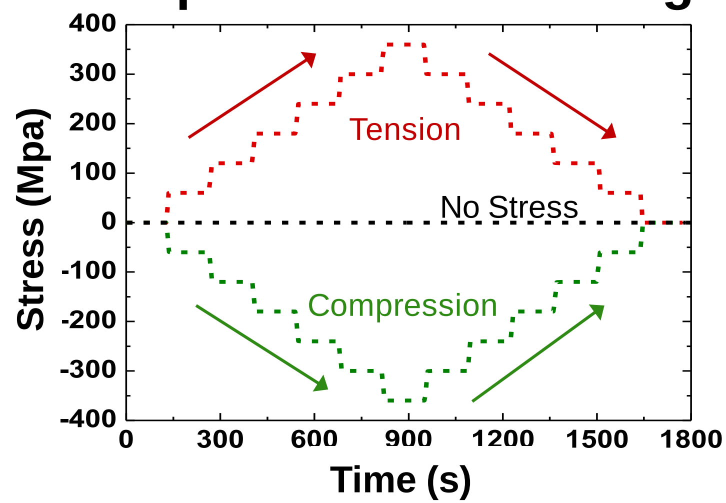


Stabilization → **Stressing**

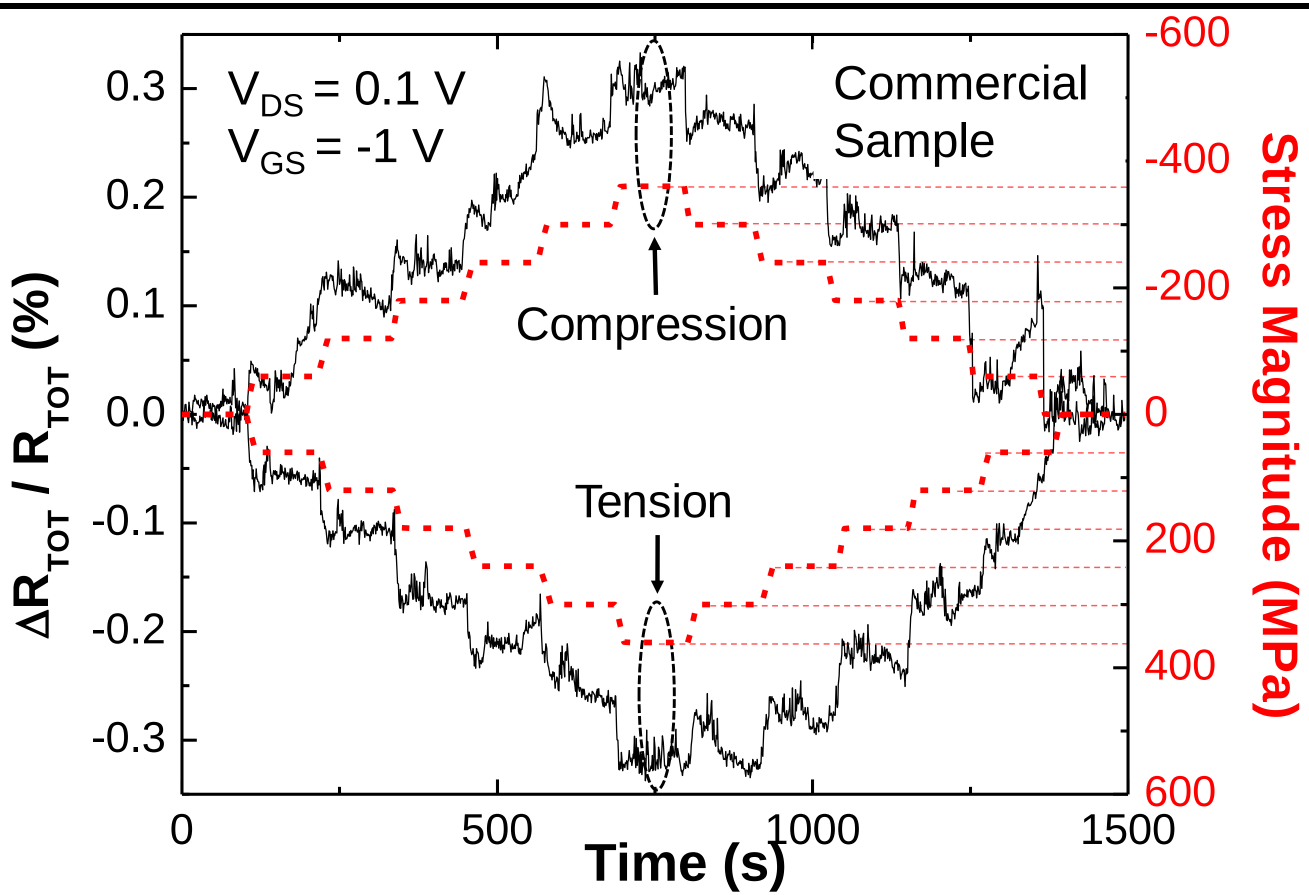
Filtered UV On



4-point Wafer Bending



Measured Piezoresistance

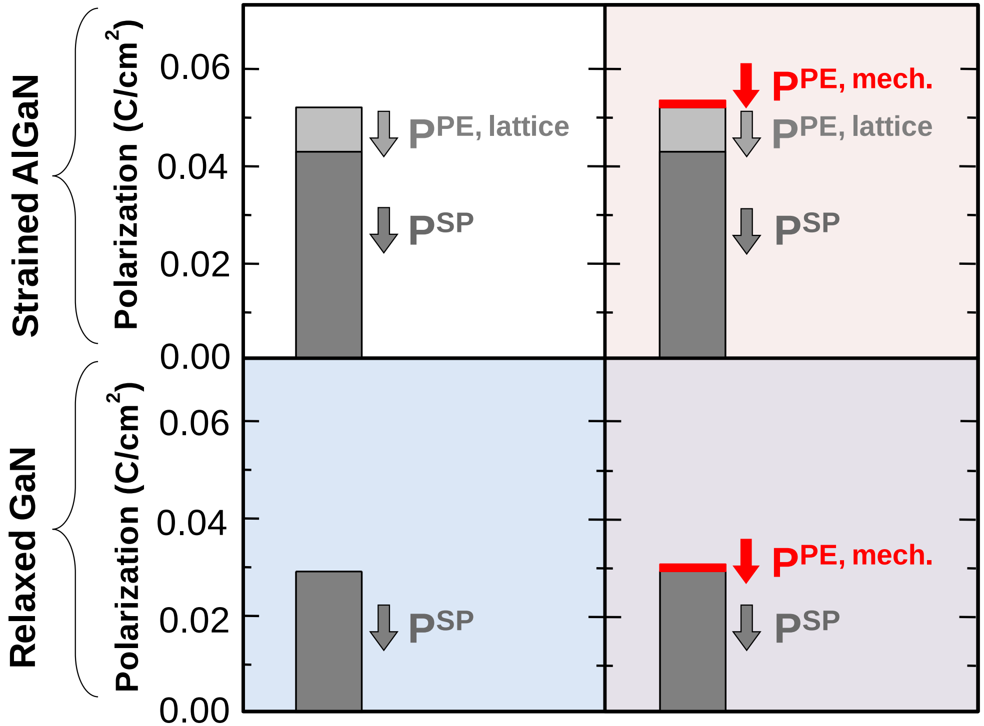


	π- Coefficient
GaN HEMT	**~1 % / GPa**
Si nMOSFET	**~32 % / GPa**

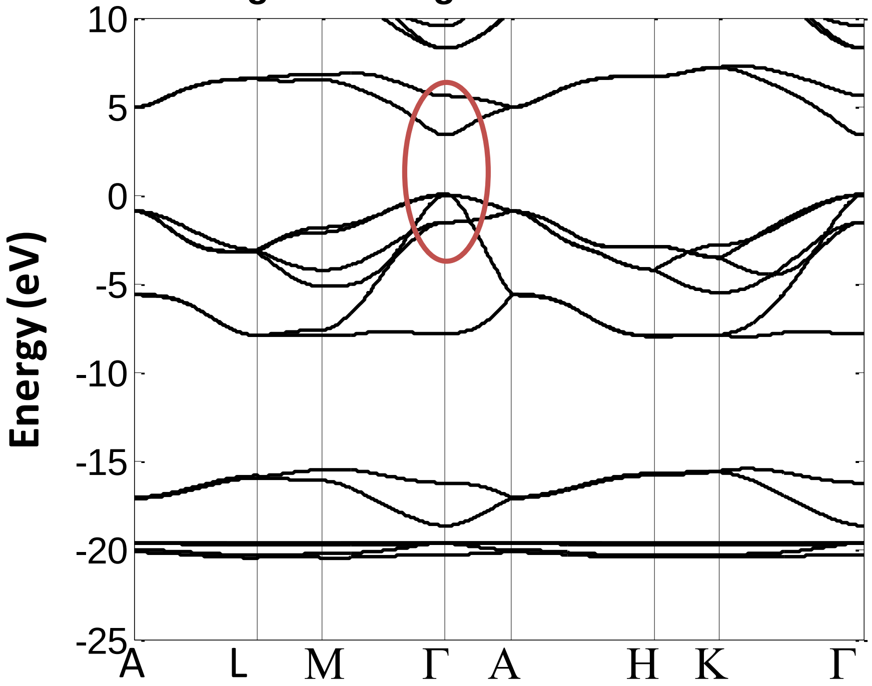
Change in Channel Resistivity

$$\rho_{2DEG} = \frac{1}{e n_s \mu_s}$$

Change in n_s

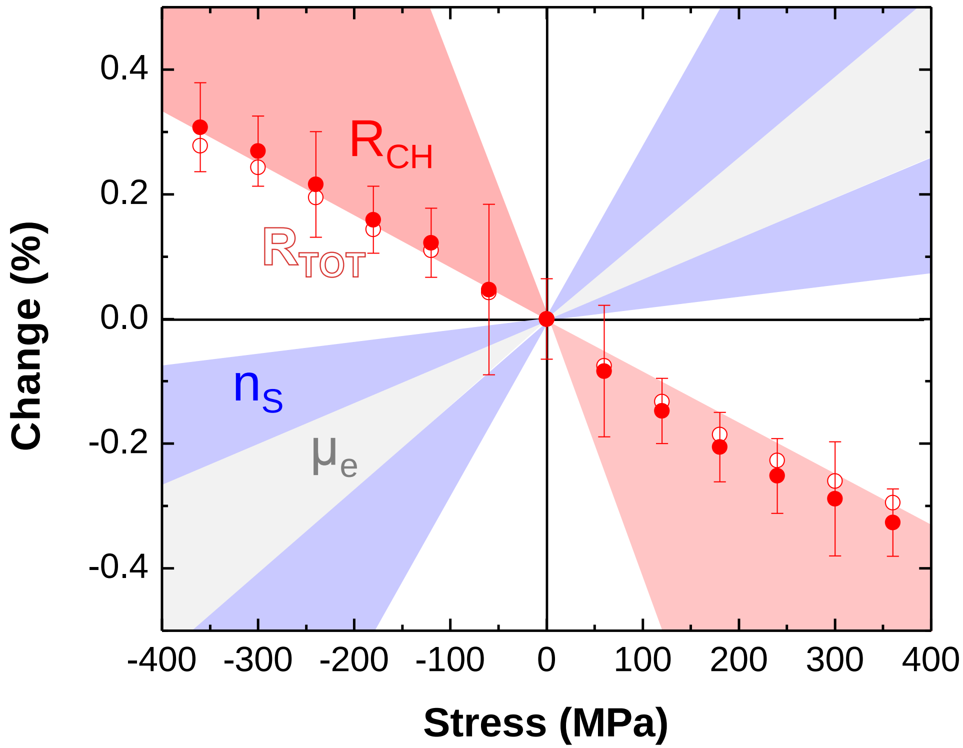


Change in μ_s



T. Yang, et al., JJAP 1995.

Experiment and Simulation



$$R_{TOT} = R_{CH} + R_S + R_D$$

$$\frac{\Delta R}{R} = -\frac{\Delta n_s}{n_s} - \frac{\Delta \mu_e}{\mu_e}$$

$$GF = \frac{\Delta R/R}{\varepsilon}, \qquad \varepsilon = \text{Strain}$$

GF = -2.8 ± 0.4

- R_{CH} extracted after accounting for S/D resistance (~ 0.5 Ω-m), resulting in a 10% shift in ΔR/R (better fit to simulation)
- Weighted Total Least Square regression used to extract GF and to give an overall GF uncertainty

Summary

- More accurate gauge factor measured after stabilization of device resistance with
  - R_{SD} correction
  - Weighted Total Least Square regression

- GaN HEMT gauge factor (GF = 2.8 ± 0.4) much smaller than Si nMOSFET (GF = 54)
  - Small change in mobility with stress (small m^* change)
  - Small change in 2DEG polarization

A. D. Koehler, A. Gupta, M. Chu, S. Parthasarathy, K. J. Linthicum, J.W. Johnson, T. Nishida, and S. E. Thompson, "Extraction of AlGaN/GaN HEMT Gauge Factor in the Presence of Traps" IEEE Electron Device Letters, accepted for publication (EDL-2010-03-0438.R1), in press.

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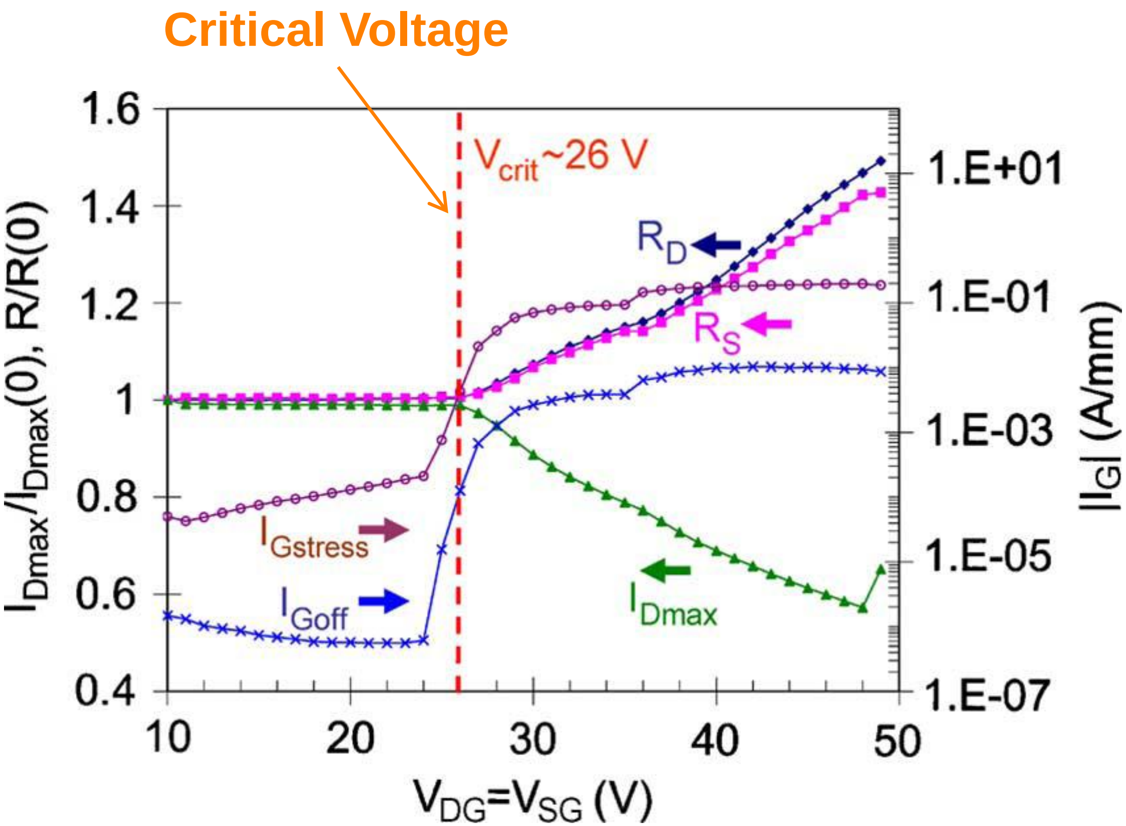
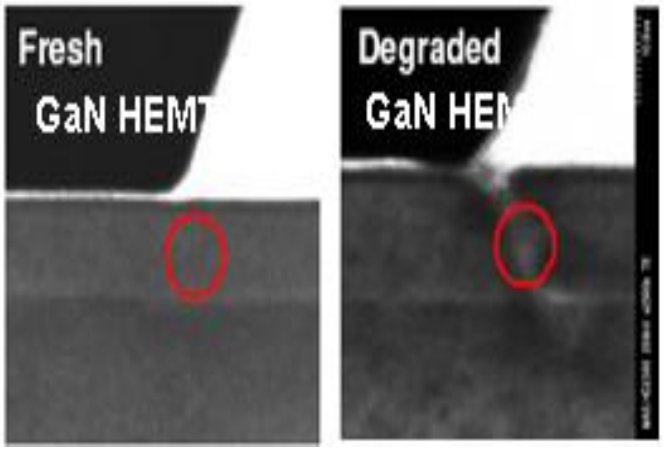
GaN HEMT I_G Degradation



J. W. Joh, *et al.*, "*EDL,* vol. 29, pp. 287-289, Apr 2008.

Defect formation

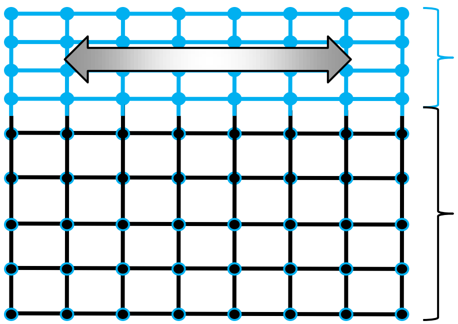


J. A. del Alamo *et al.*, DRIFT MURI, 2009.

- Hypothesis: Field-induced stress causes degradation
- Our goal: Systematically investigate effect of stress on gate leakage

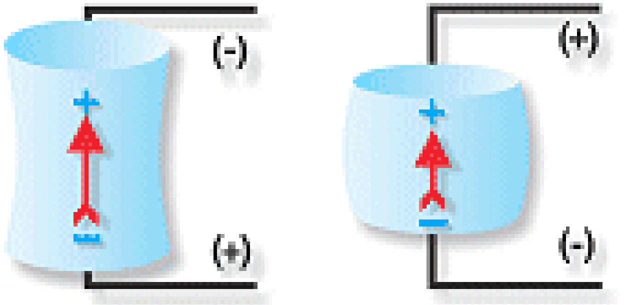
Stressors in GaN HEMT During Operation

Process Stressors
(Lattice Mismatch)



2.8 GPa Biaxial Tensile

Bias Stressors
(Inverse Piezoelectric Effect)



~500 MPa Biaxial Tensile
(V_{GS} = 30 V)

~3.5 GPa
Biaxial Tensile

Thermal Effects
(Self Heating)

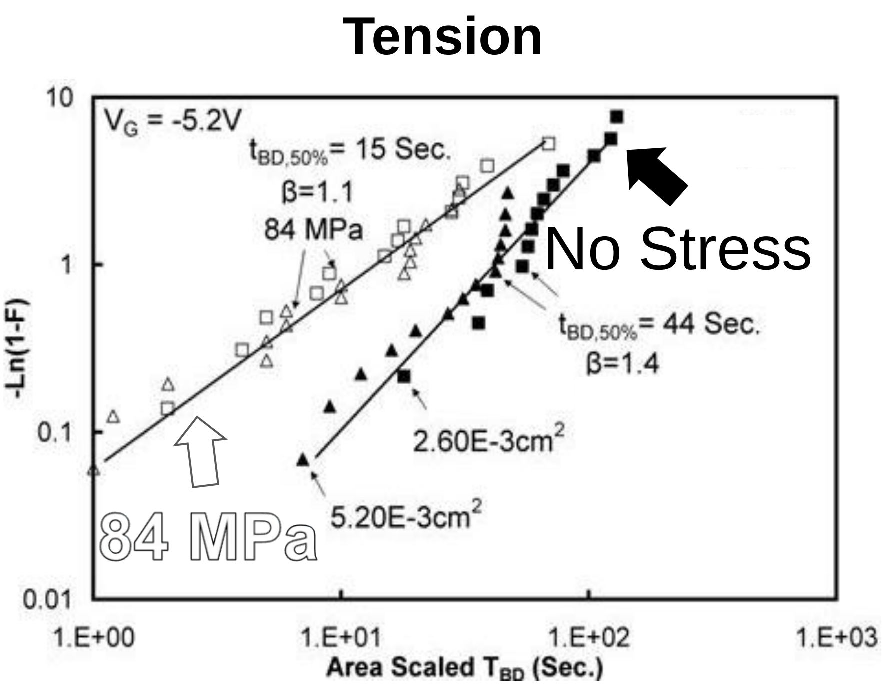
Yield strength: 15 GPa [1] → 0.2 GPa [2]

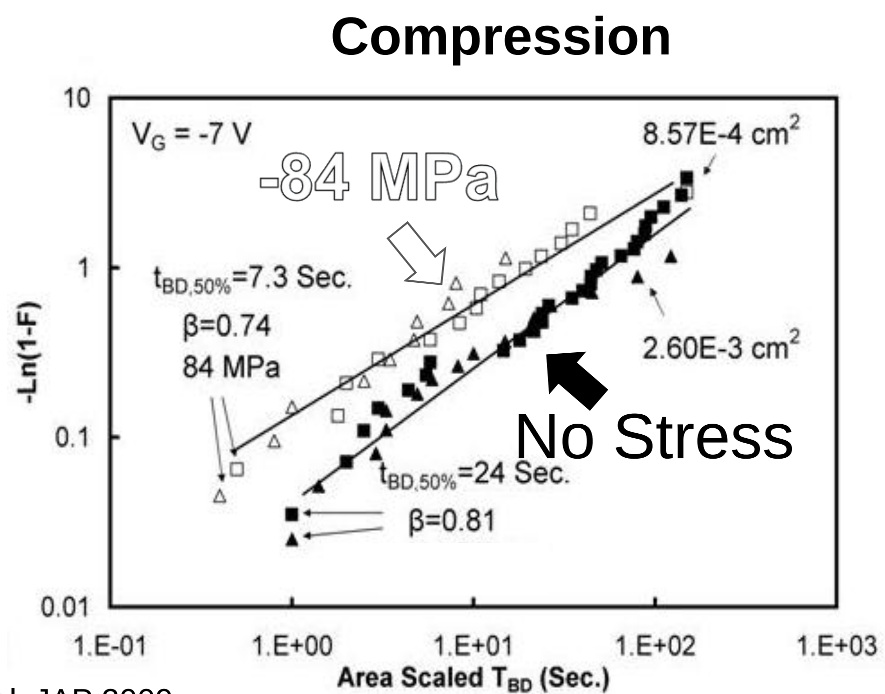
Temperature: 27 ºC → 1000 ºC

operating temperature
100 ºC to 400 ºC [3]

[1] R. Nowak,*et al*, APL 1999.
[2] I. Yonenaga, *et al*, JAP, 2001.
[3] D.S. Green, et al, pssc, 2008

Si Background: Stress on Reliability (HfSiON)



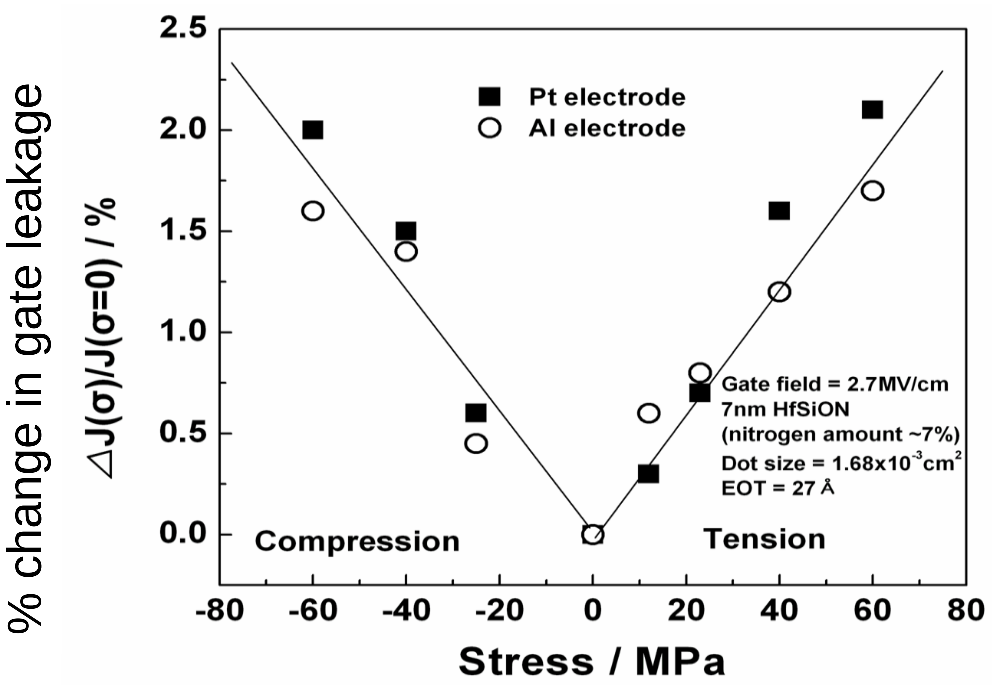


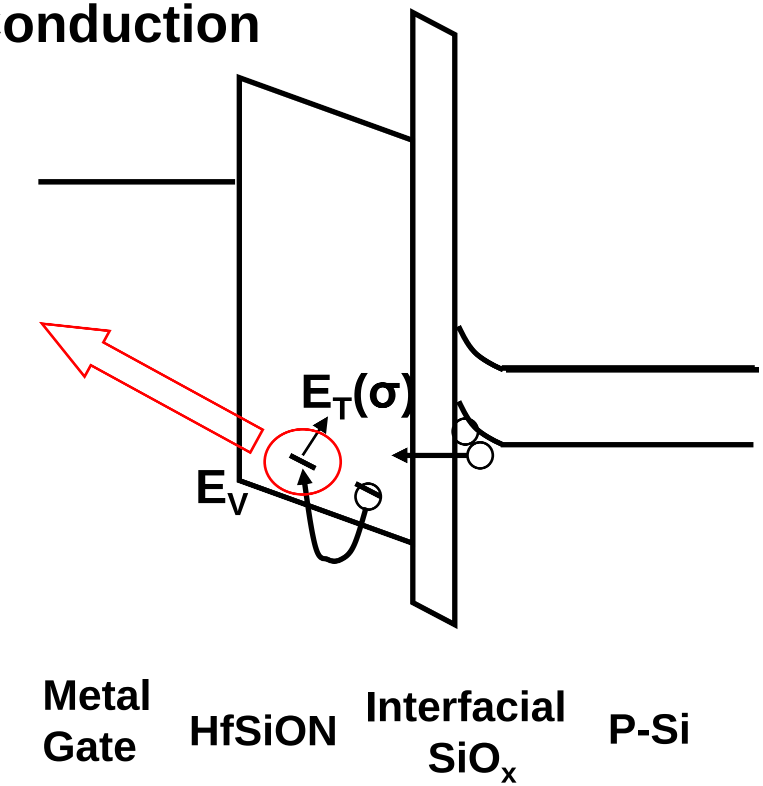
Y.S. Choi et al. JAP 2009

- Large V_G bias applied to electrically stress the device
- Both tensile and compressive stress degrade t_{BD}
- TDDB is destructive and requires many samples (impractical for GaN HEMT) analysis

Si Background: Stress on Trap Energy (HfSiON)

Hole Poole-Frenkel Conduction



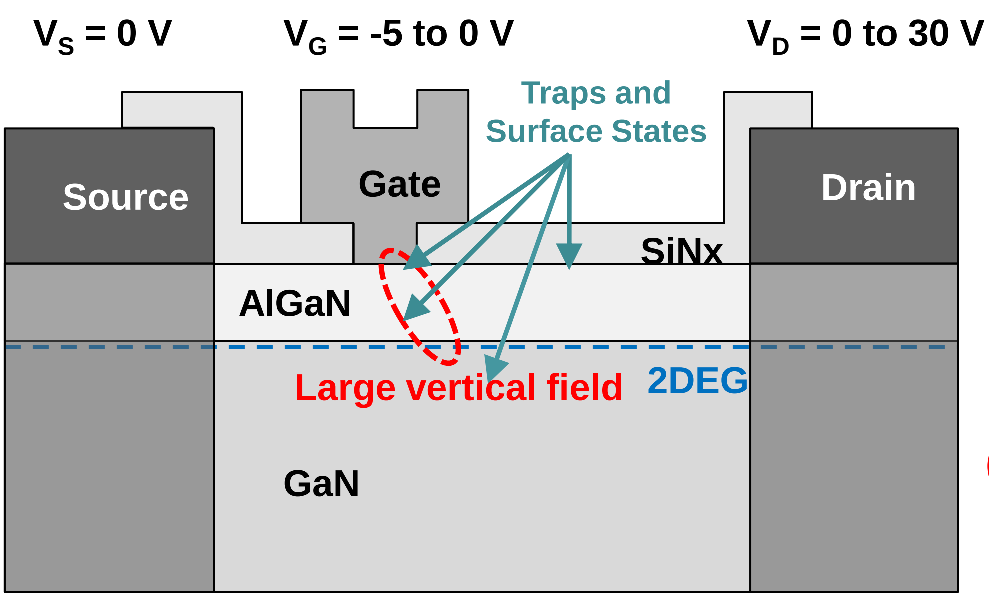


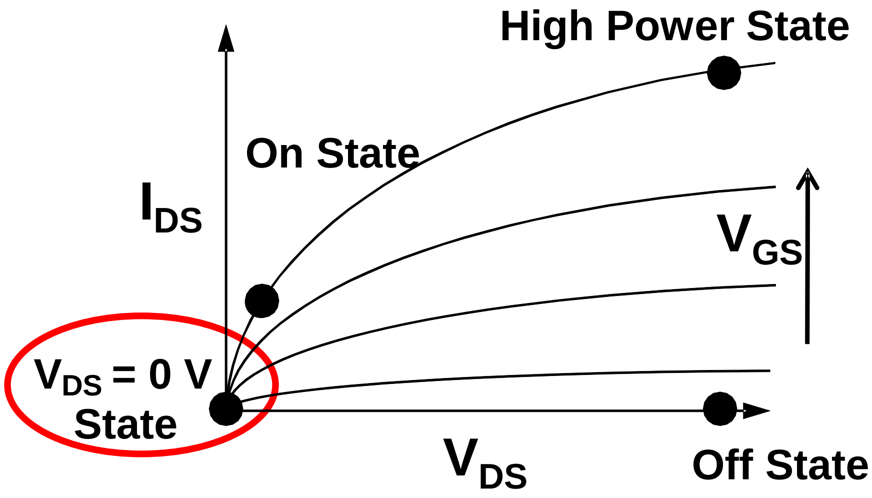
S.Y. Son, Y.S. Choi, et al APL 2008

- Nondestructive gate current measurements at small V_G bias give insight into effect of stress on gate leakage and reliability

- **Stress can change trap activation energy**

Stress on GaN HEMT I_G Degradation

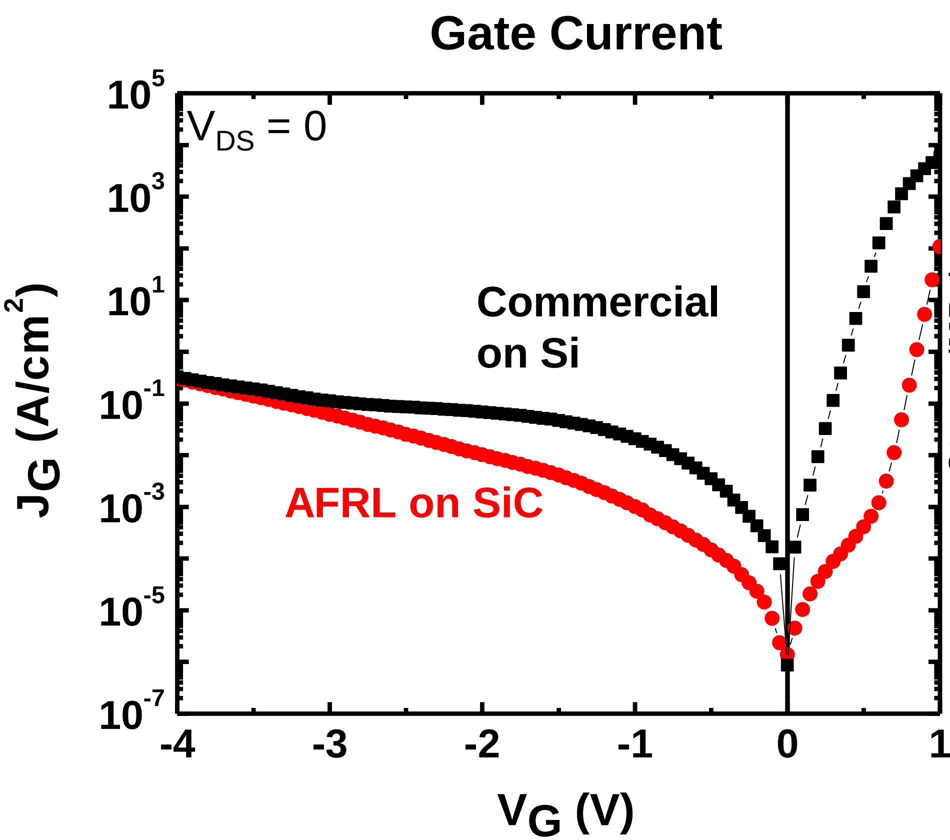


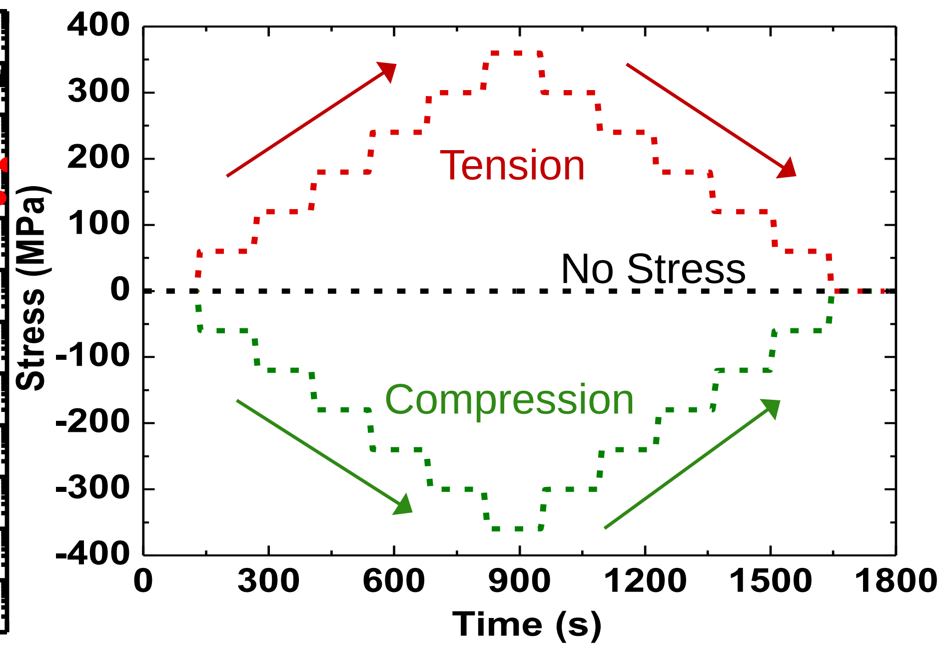


- Large vertical field creates stress in GaN HEMT (inverse piezoelectric effect)
  - Alter trap activation energy
  - Generate traps: approaching yield strength, *f*(temp)?
    - Increase in 1/f noise (Dr. Bosman)
    - Changes in gate interface chemistry (Dr. Ren)

Isolate effect of field (V_{DS} = 0 state) to investigate effect of stress on gate leakage for varying V_G biases to determine predictors to catastrophic failure

J_G Measurement





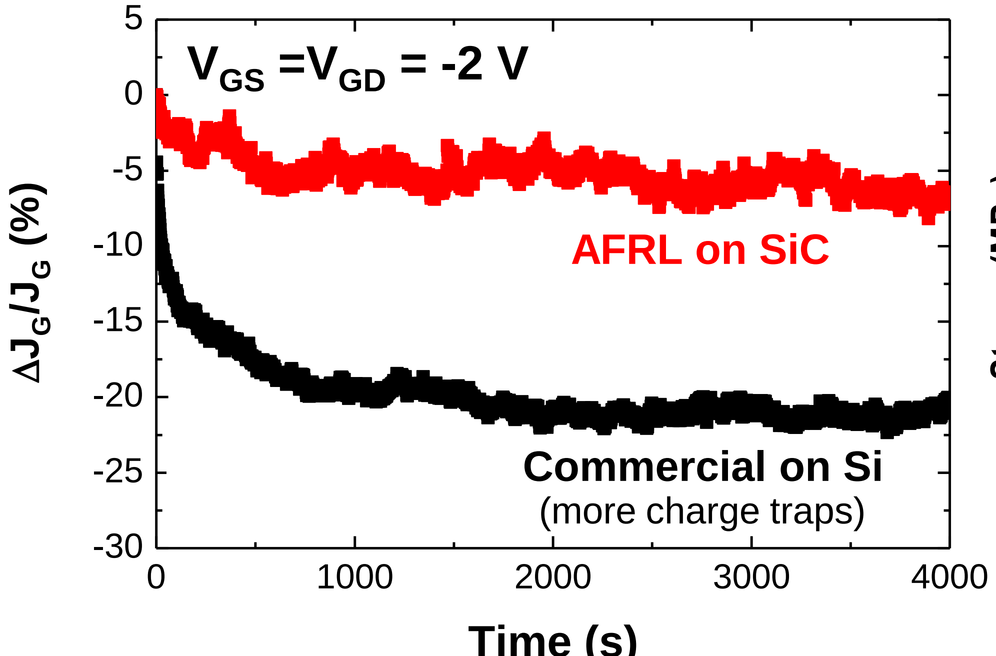
- AFRL has less gate leakage than the commercial sample
- Measure stress dependence of gate leakage

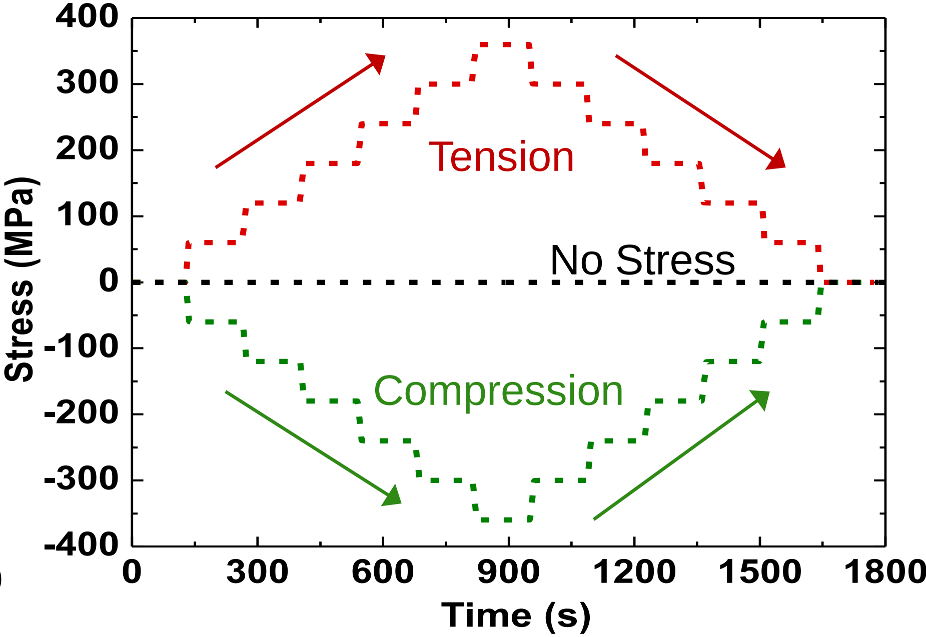
J_G Measurement Procedure

Stabilization | **Stressing**

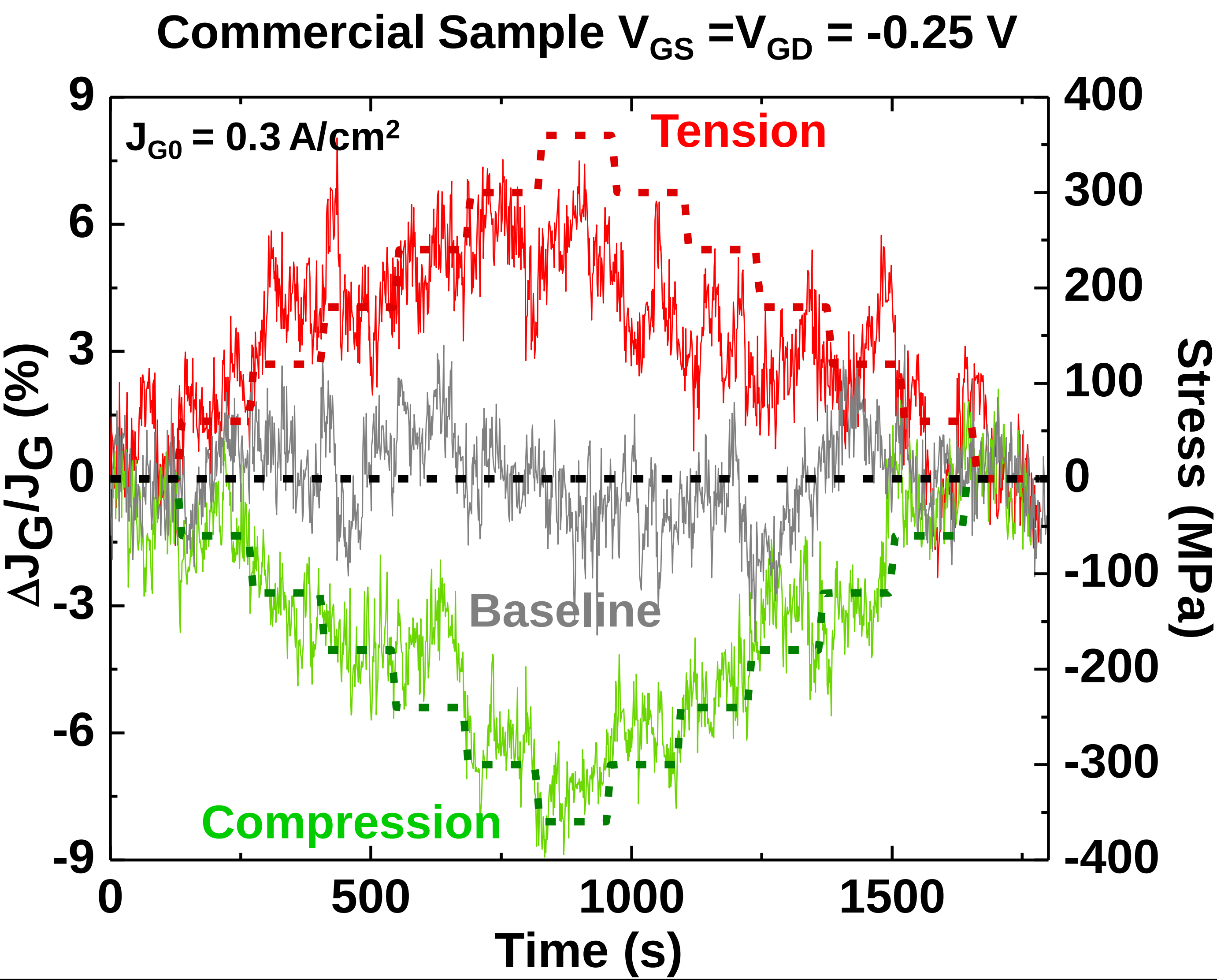
Bias device in dark → Wait until steady state → Incrementally apply stress

constant V_G | fill all available traps | measure $\Delta J_G/J_G$



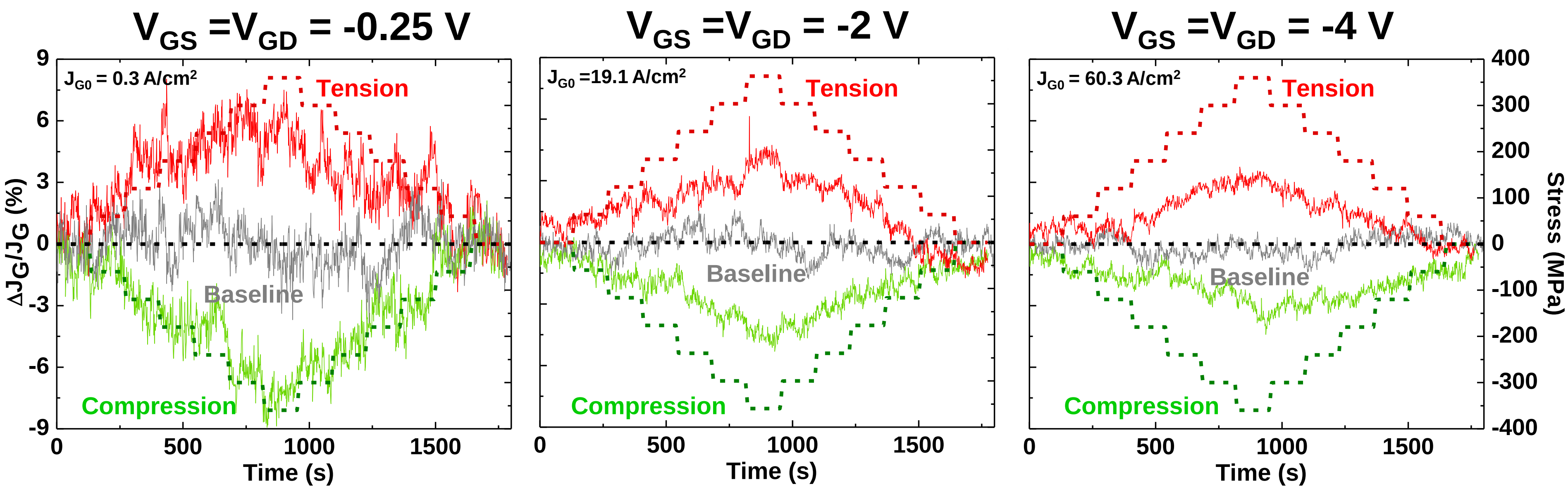


J_G Stress Measurement Results



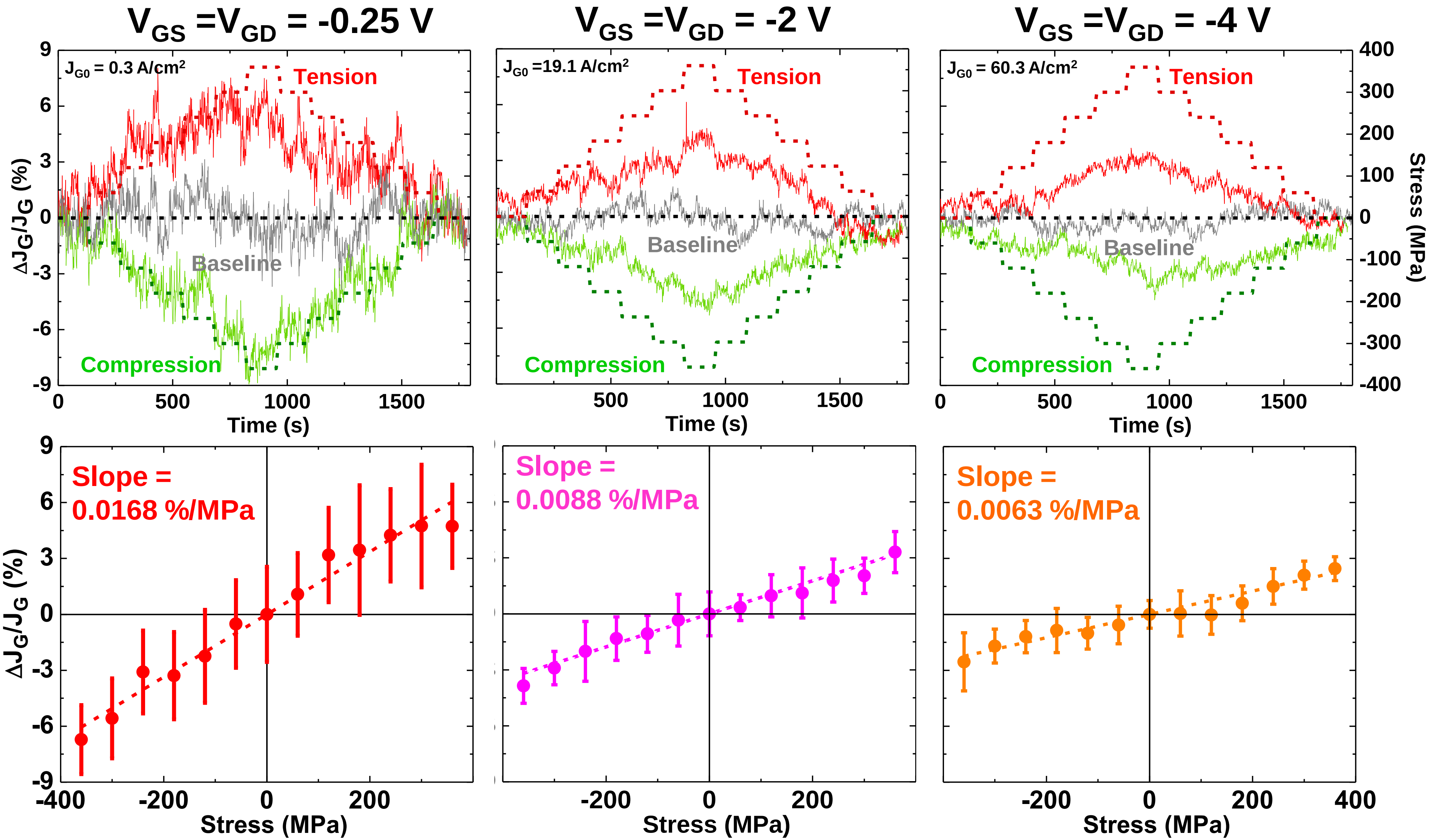
J_G Stress Measurement Results (Commercial)

T = 293K



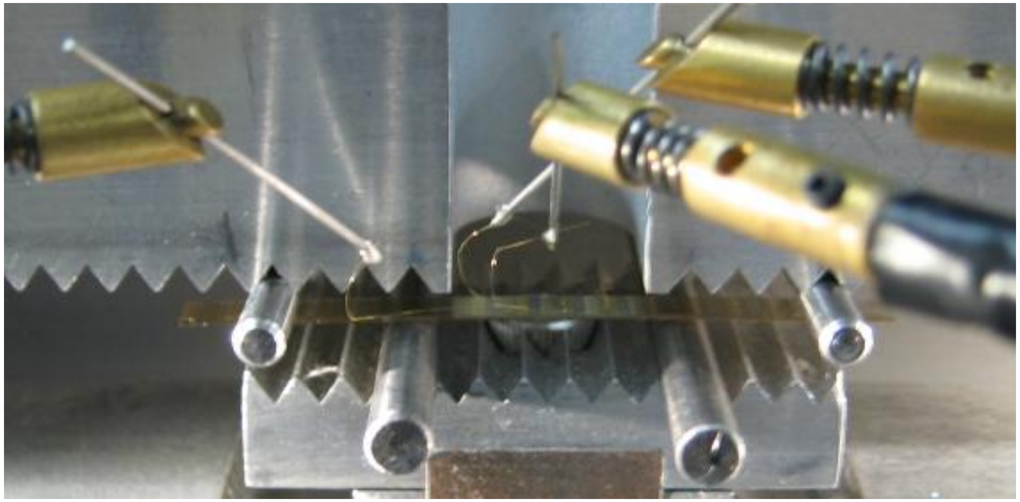
- Tensile stress increases gate current
- Compressive stress decreases gate current
- Decreased sensitivity of gate current with stress at higher gate field

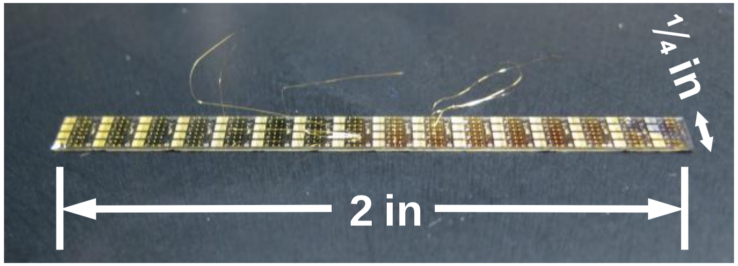
J_G Stress Measurement Results (Commercial)



Bending AFRL on SiC Samples

	Substrate Young's Modulus (GPa)	Sample Thickness (µm)
Commercial on Si	169	150
AFRL on SiC	544	400

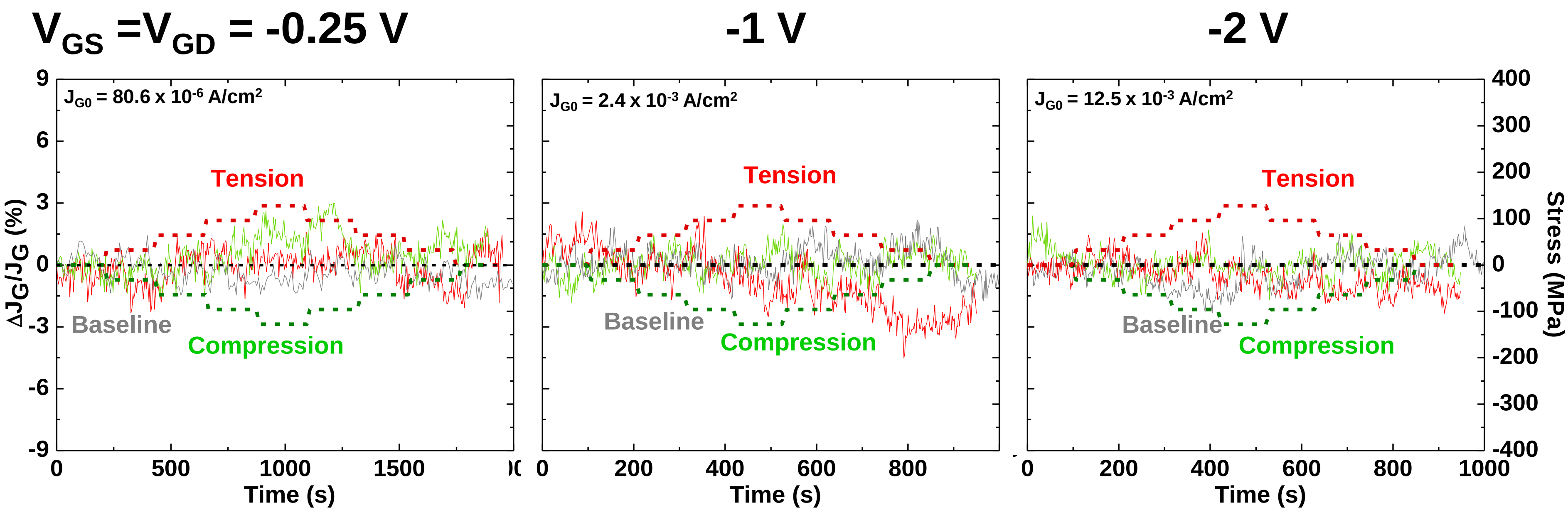




Need to bend SiC samples directly

J_G Stress Measurement Results (AFRL)

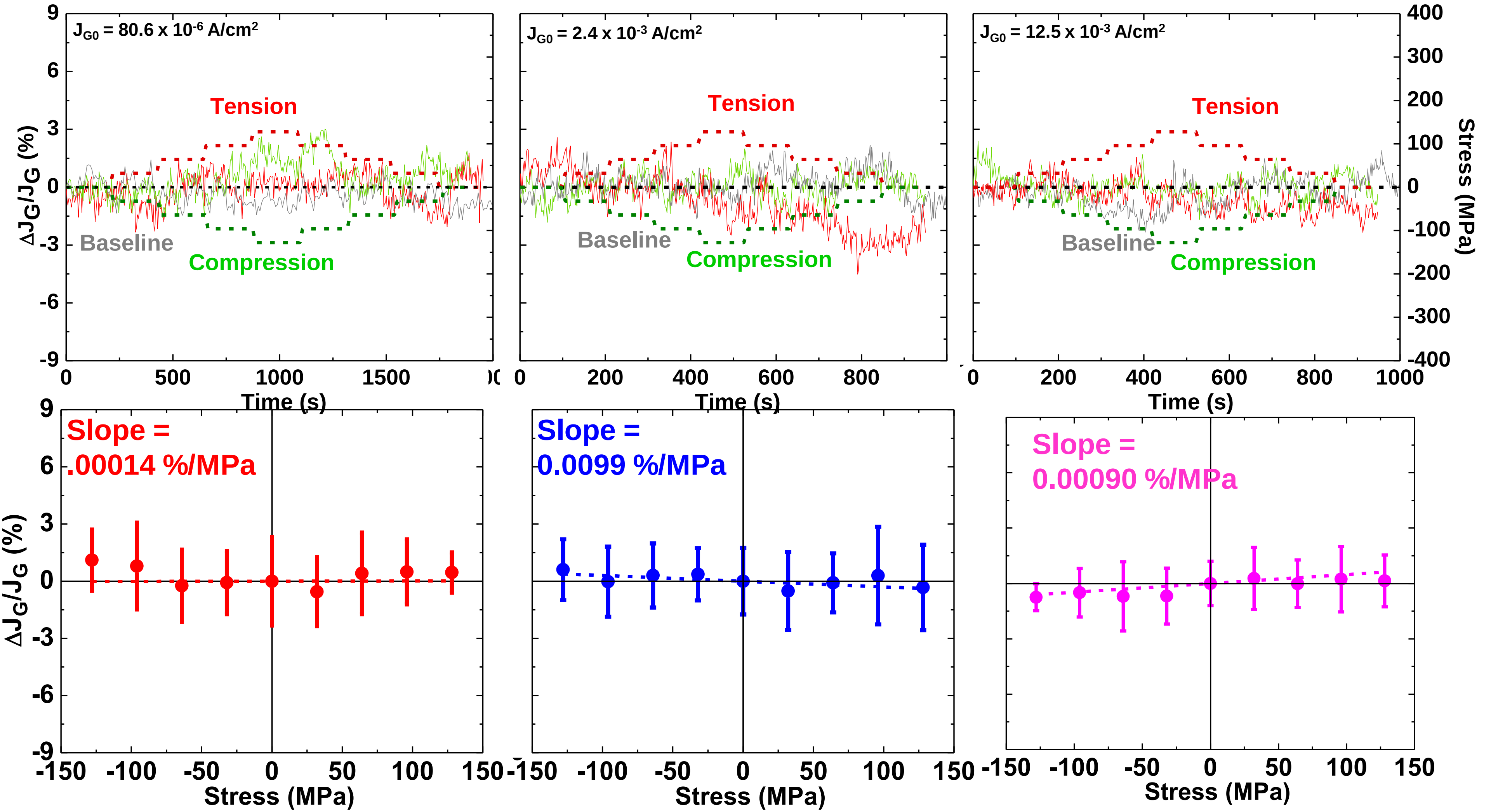
T = 293K



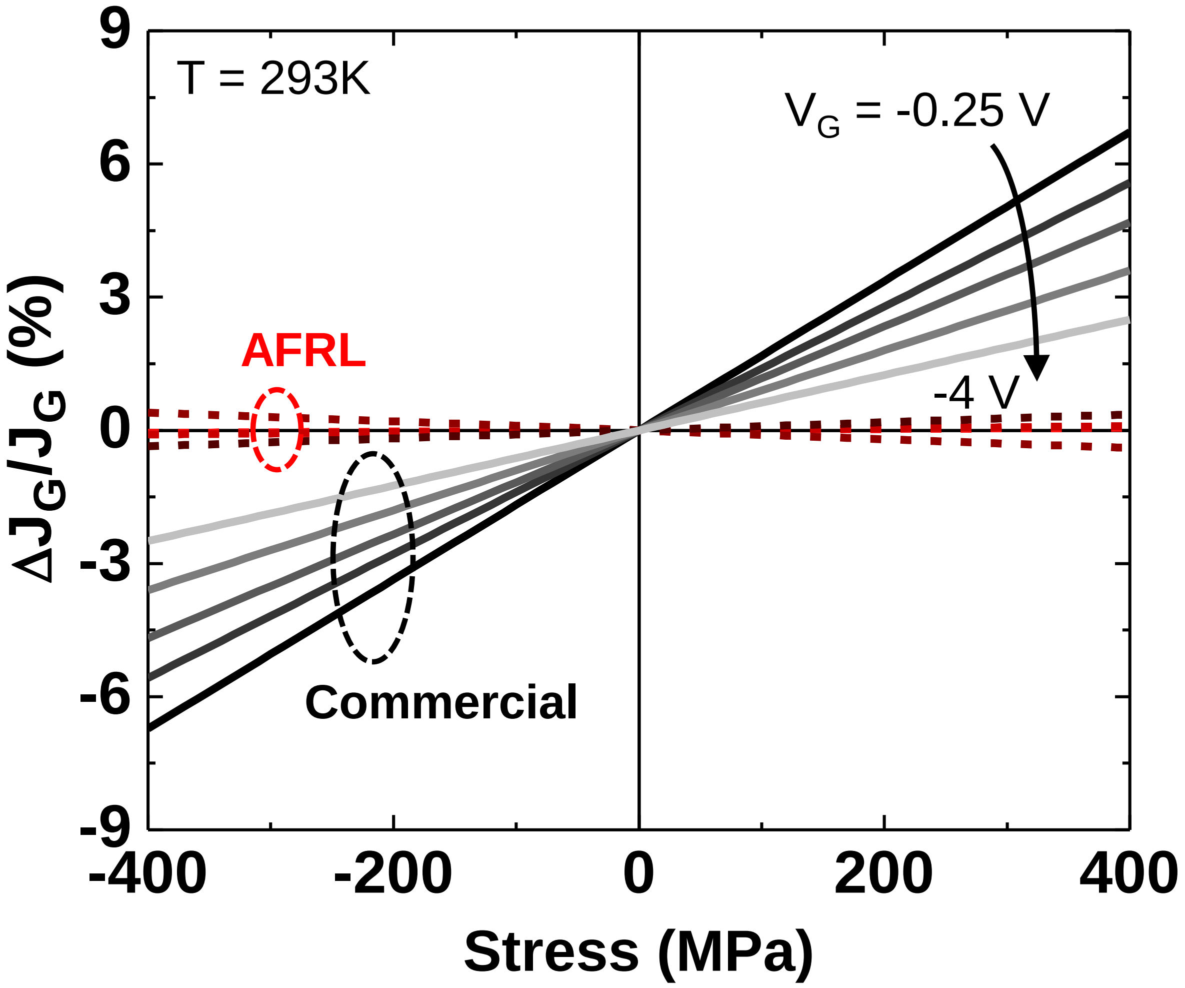
- Little/no observed change in gate current with stress up to +/- 120 MPa
- Next step: Increase applied stress to … 360 MPa

J_G Stress Measurement Results (AFRL)

$V_{GS} = V_{GD}$ = -0.25 V | -1 V | -2 V



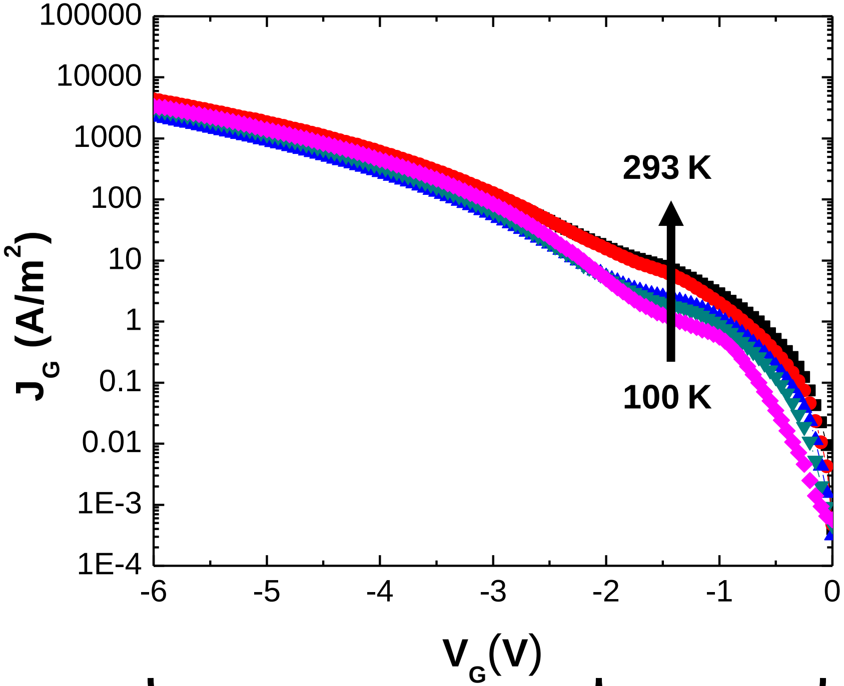
J_G Stress Effect: Commercial vs. AFRL



Why is there a difference between the two samples?

J_G Temperature Dependence

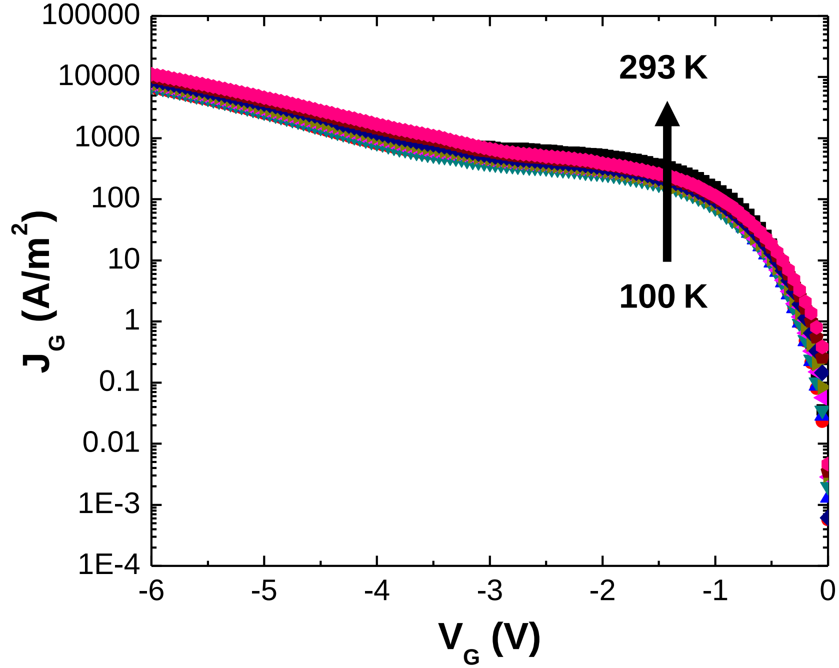
Commercial



Direct tunneling

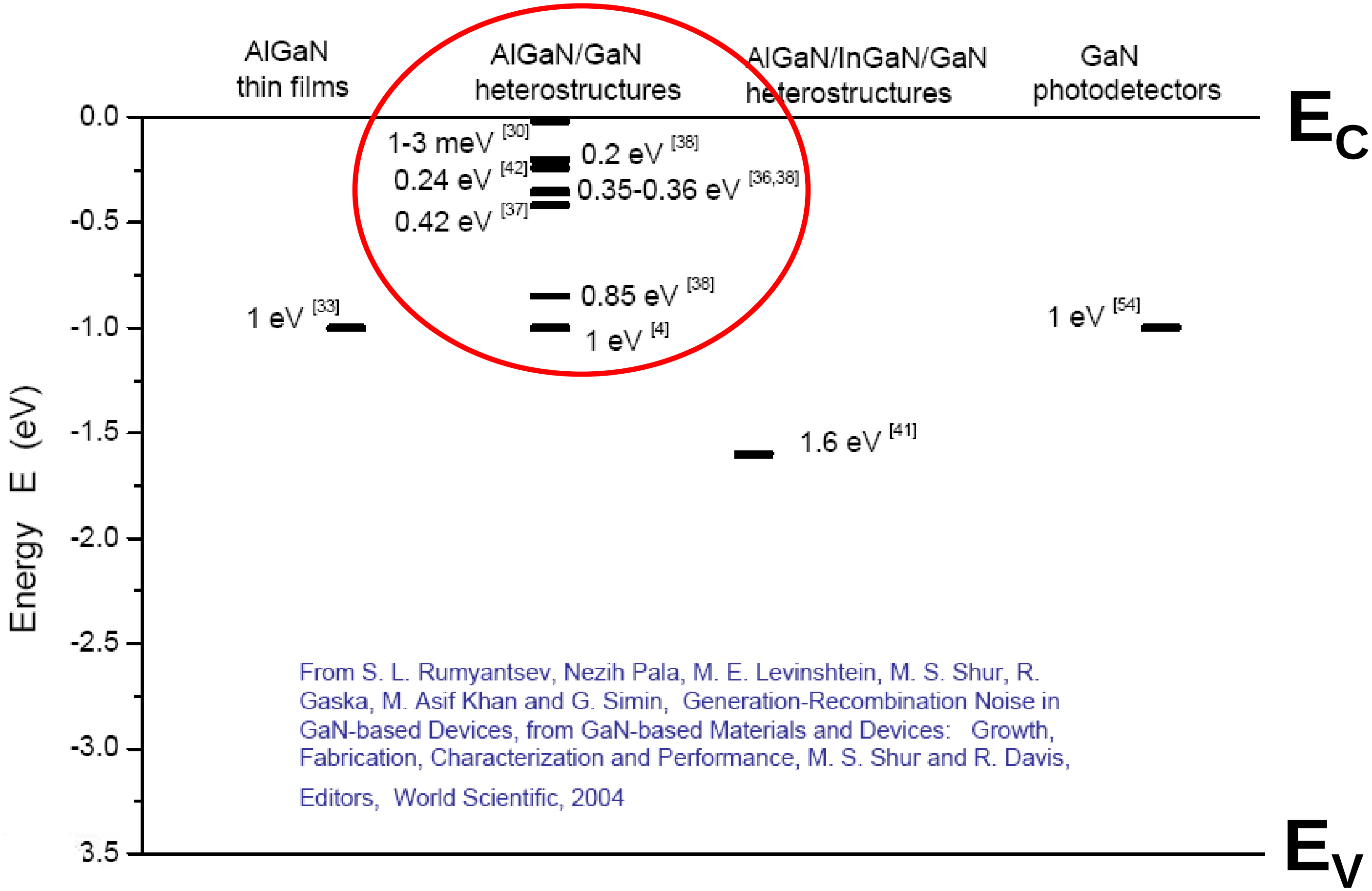
Trap-assisted tunneling

AFRL



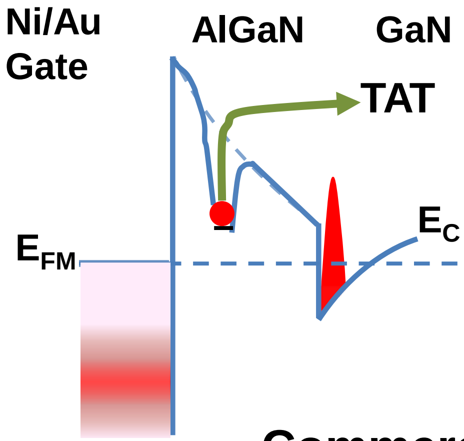
Direct tunneling

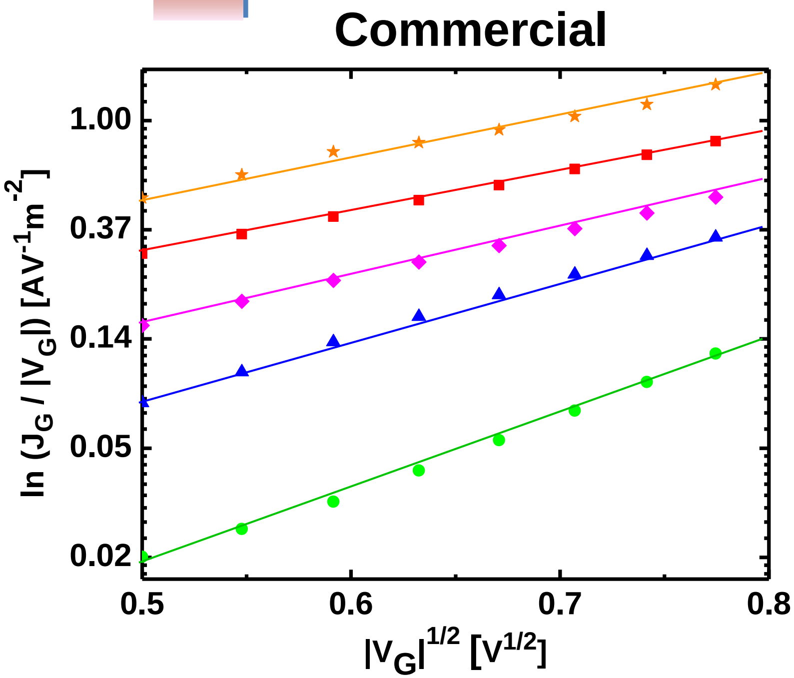
Traps in AlGaN/GaN HEMT



- Many AlGaN/GaN traps are close to the conduction band edge contributing to PF tunneling

Poole Frenkel Tunneling





- PF emission: trap to conduction band
- Linear fit shows Poole Frenkel emission

$$\text{Ln}\,(J/E)\ \alpha\ E^{1/2}$$

J. Frenkel , PHYSICAL REVIEW ,54 ,1938

- P-F model :

$$J = CE\exp\left[-\frac{q\left(\varphi_t - \sqrt{\frac{qE}{\pi\varepsilon_0\varepsilon_s}}\right)}{kT}\right]$$

φ_T – trap level energies

	φ_T
This Work	0.31±0.14 eV
Zhang *et al.* JAP, 2006	0.30±0.03 eV

Summary

- Gate current increases with tensile stress and decreases with compressive stress at specific bias
  - More pronounced for sample (commercial) that exhibits PF tunneling at low bias
  - Stress sensitivity larger at lower biases for sample with PF tunneling
- At least two mechanisms
  - Direct tunneling dominates at higher biases
    - Applicable for both HEMT processes (commercial, AFRL)
  - Trap-assisted tunneling at lower biases
    - Temperature dependent (commercial)
    - Extracted trap energy ~0.31 eV.

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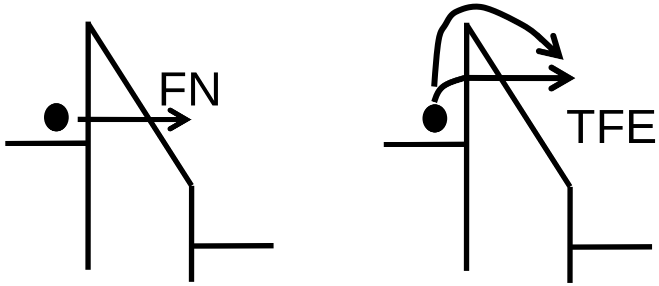
Gate Tunneling in HEMT

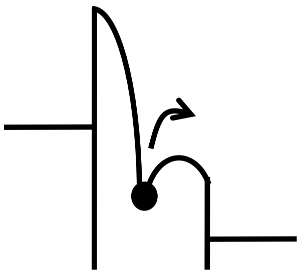
Direct tunneling

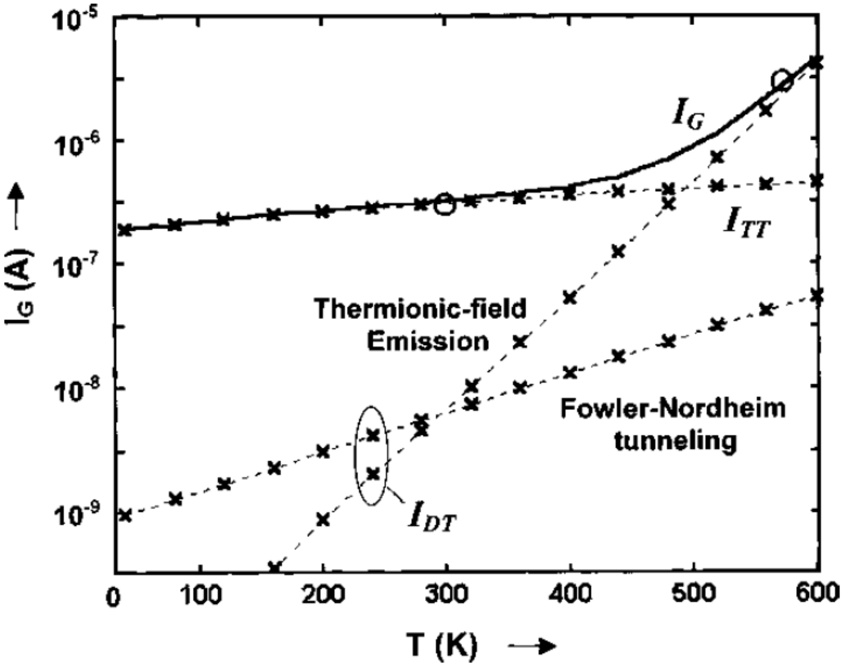
(Fowler-Nordheim &
Thermionic-Field Emission)



Trap-assisted tunneling

(Poole-Frenkel)





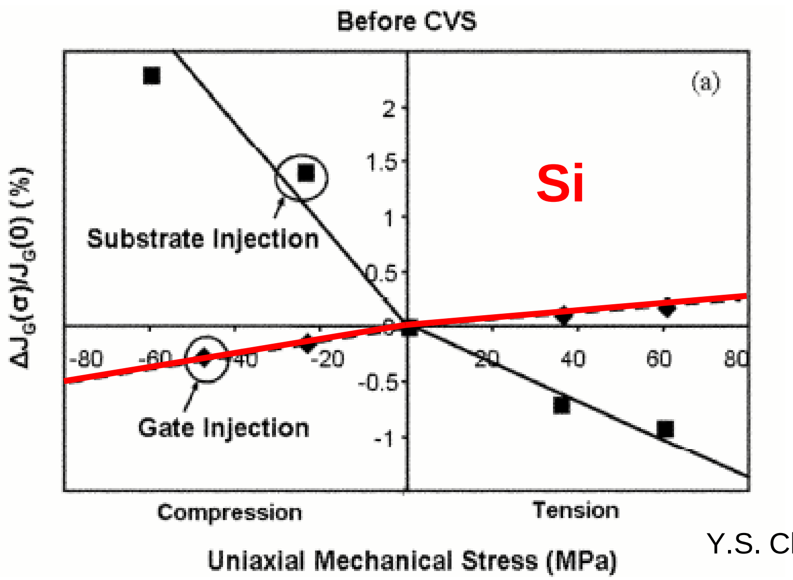
D.M. Sathaiya et al., APL 2003.

Which mechanism dominates depends on:

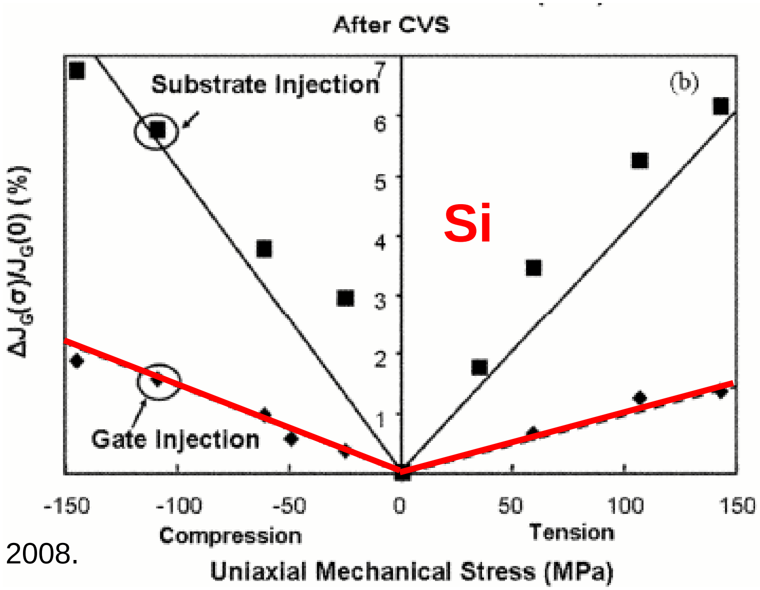
- Thickness of AlGaN layer
- Electric field across the AlGaN layer
- Quality of the AlGaN layer
- temperature

Si Background: Gate Leakage vs. Stress

Direct tunneling



Trap-assisted tunneling



Y.S. Choi, et al., APL 2008.

Gate injection:
Metal work function change

Substrate injection:
Si conduction band splitting
Electron out-of-plane effective mass

E_A decreases under both tension and compression

Direct Tunneling: FN Tunneling

Analytical model:

$$J = \frac{q^2\left(m_e / m_n^*\right)}{8\pi h\phi_b} E^2 \exp\left(-\frac{8\pi\sqrt{2m_n^*\left(q\phi_b\right)^3}}{3qhE}\right)$$

[J. Appl. Phys. 99. 023703]

Primary parameters:

1. Electric field (E)
   - Sentaurus Device simulation
2. Barrier height (ϕ_b)
   - Effect of stress on metal work function
   - Nickel on top of AlGaN
   - Barrier height lowering due to image force is taken into consideration
3. Electron out-of-plane effective mass (m_n^*)
   - Tight binding calculation

Direct Tunneling: Thermionic-Field Emission

$$J = \underbrace{\frac{A^* T}{k}\int_{E_{\min}}^{q\phi_b} dE \left\{F_m(E)T_r(E)\left[1 - F_s(E)\right]\right\}}_{\text{Thermal-assisted tunneling}} + \underbrace{\frac{A^* T}{k}\exp\left(-\frac{q\phi_b}{kT}\right)}_{\text{Thermal emission}}$$

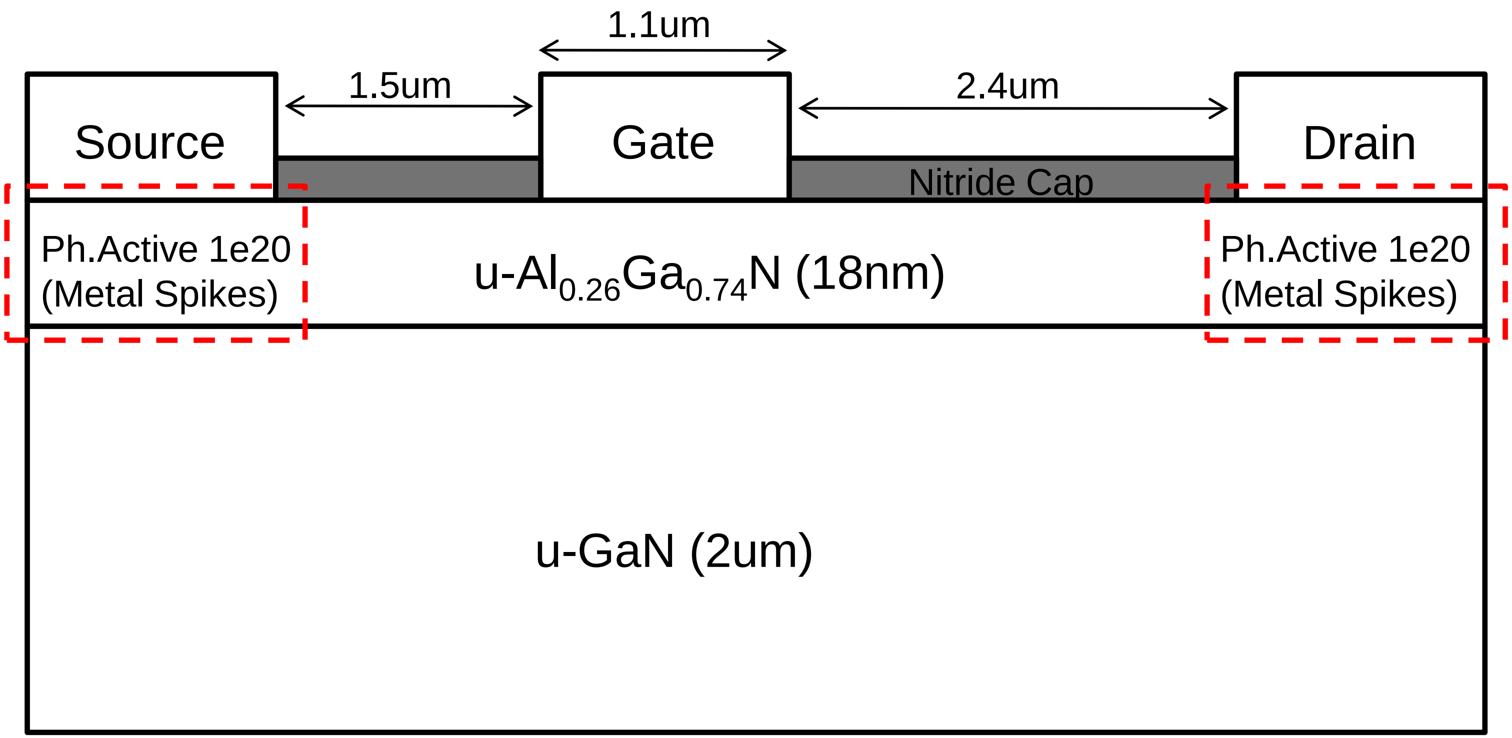
[J. Appl. Phys, vol.86, pp.3398]

Primary parameters:

1. Electrical potential (ψ)
   - Sentaurus Device simulation
2. Barrier height (ϕ_b)
   - Effect of stress on metal work function
3. Electron out-of-plane effective mass (m_n^*)
   - Tight binding calculation

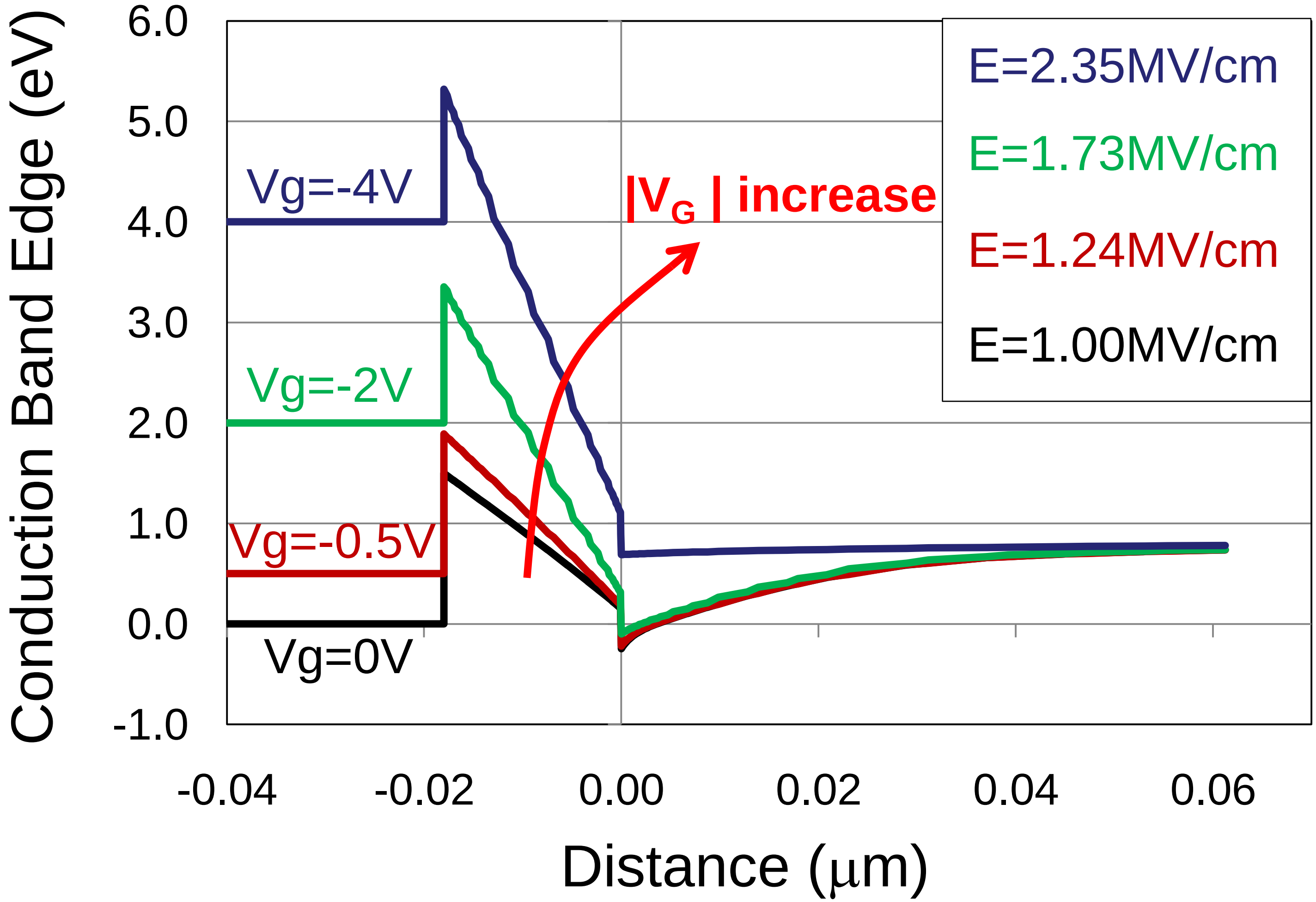
Both FN tunneling and TFE have similar dependence on stress.

Numerical Device Simulation

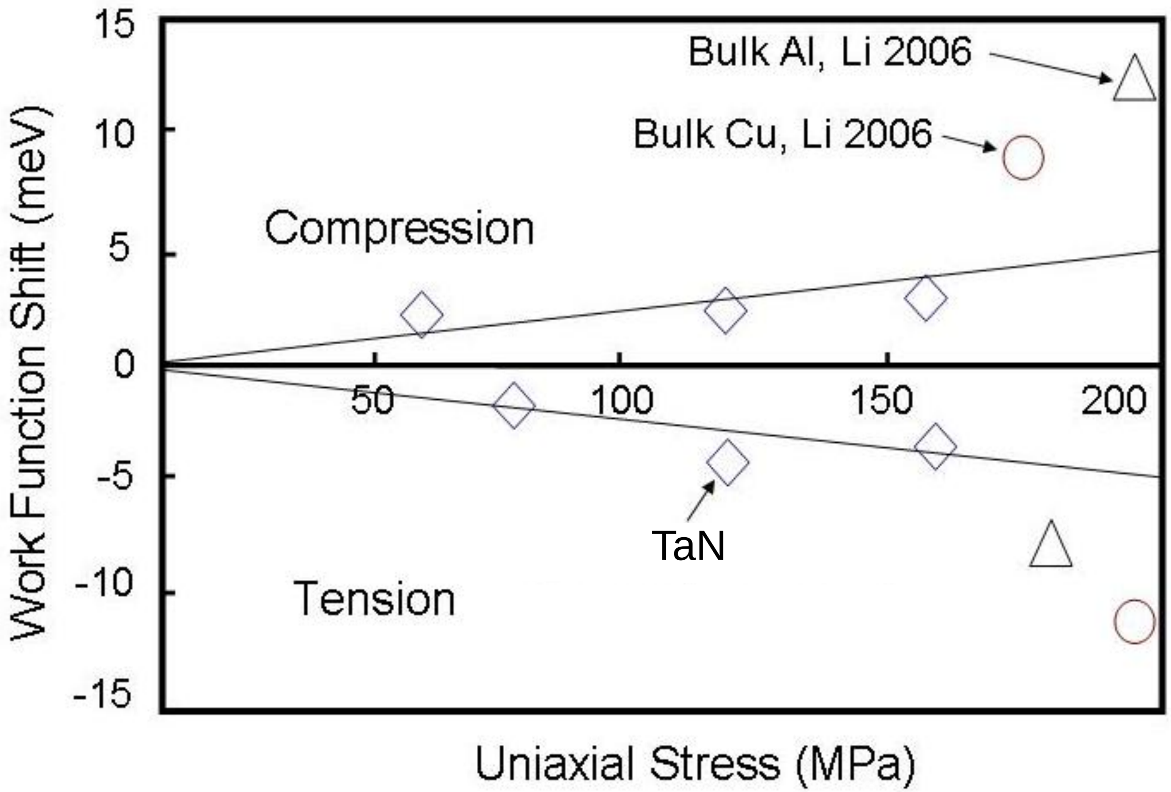


- Hydrodynamic model
- Fermi-Dirac
- Recombination(SRH)
- Aniso(Poisson)
- Mobility (DopingDep, HighFieldSaturation)
- EffectiveIntrinsicDensity(No Bandgap Narrowing)
- RecGenHeat

Band Profile from TCAD Simulation



Si Background: Metal Work Function vs. Stress



$$V_{FB} = \varphi_{MS} - \frac{Q_{OX}}{C_{OX}}$$

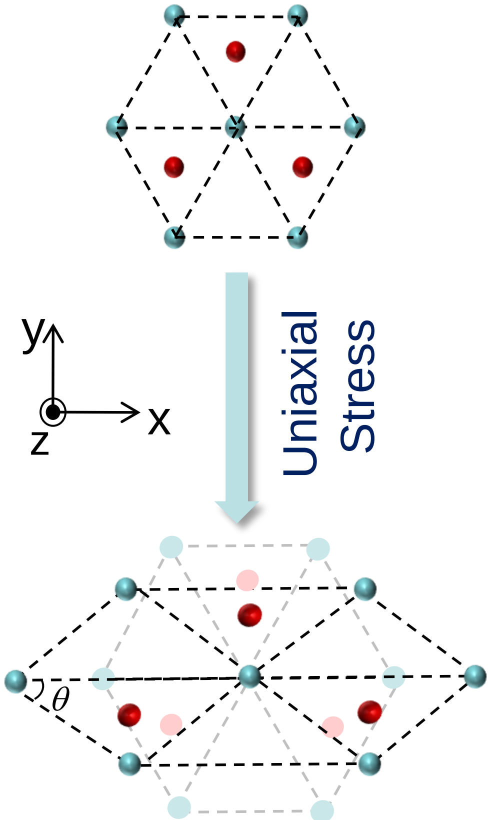
$$\Delta V_{FB}(\sigma) \approx \Delta\varphi_M(\sigma) - \Delta\varphi_S(\sigma) \approx \Delta\varphi_M(\sigma)$$

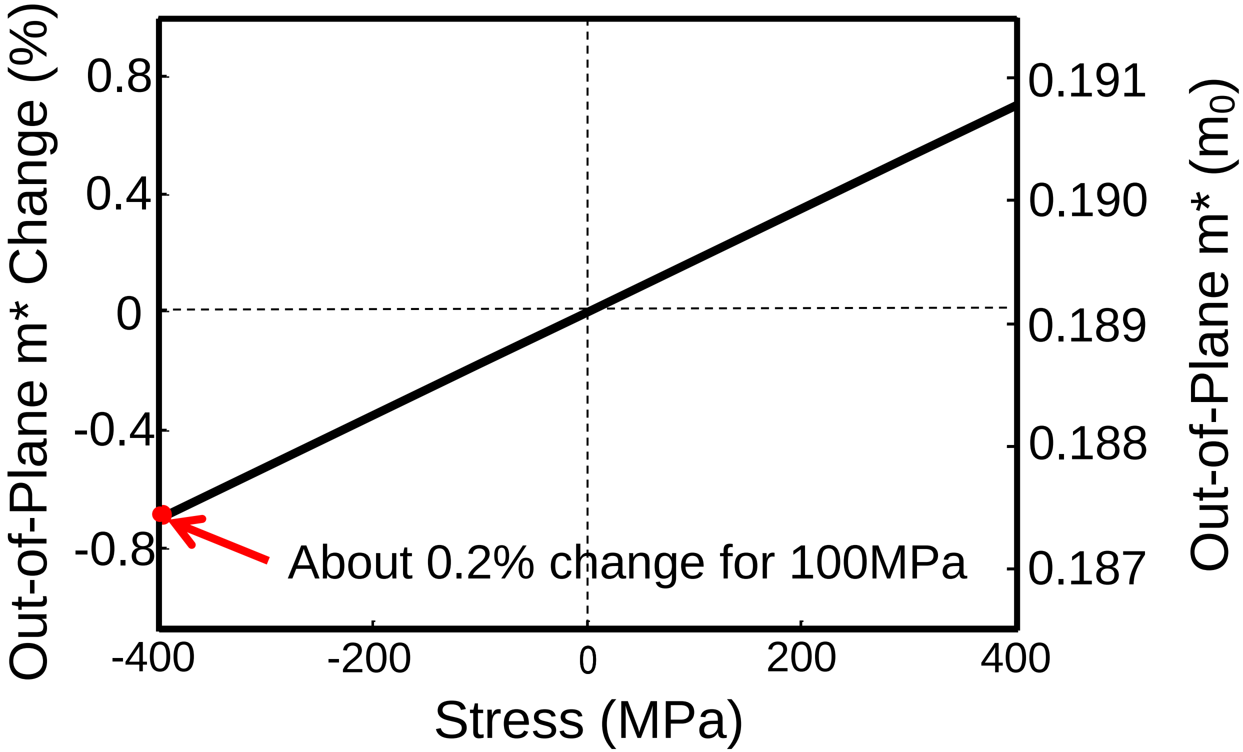
[J. Appl. Phys, vol.103, pp.064510]

The Trend:

Work-functions of different metal increase/decrease with compressive/tensile stress. ~2meV/100MPa

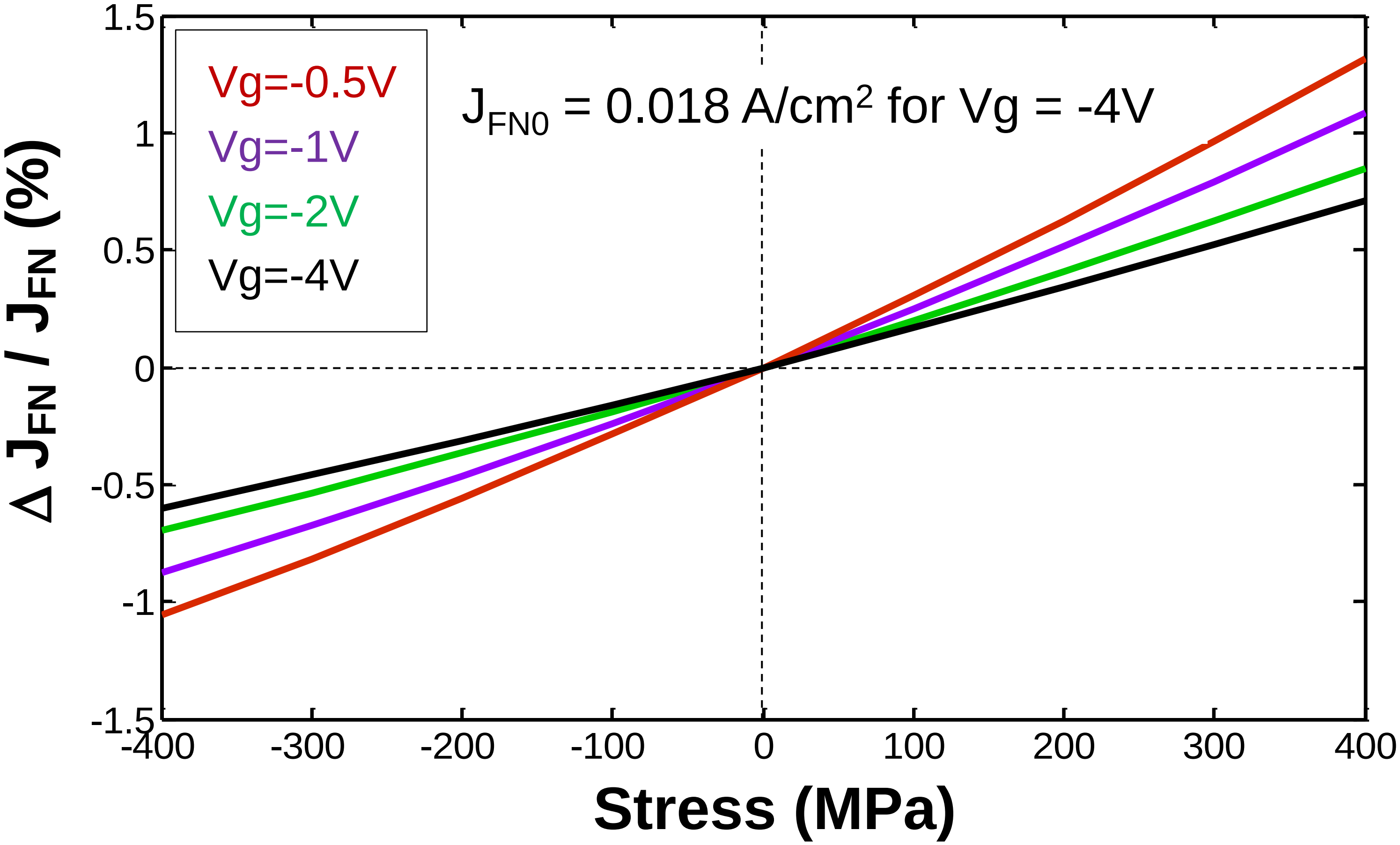
Electron out-of-plane m* in GaN





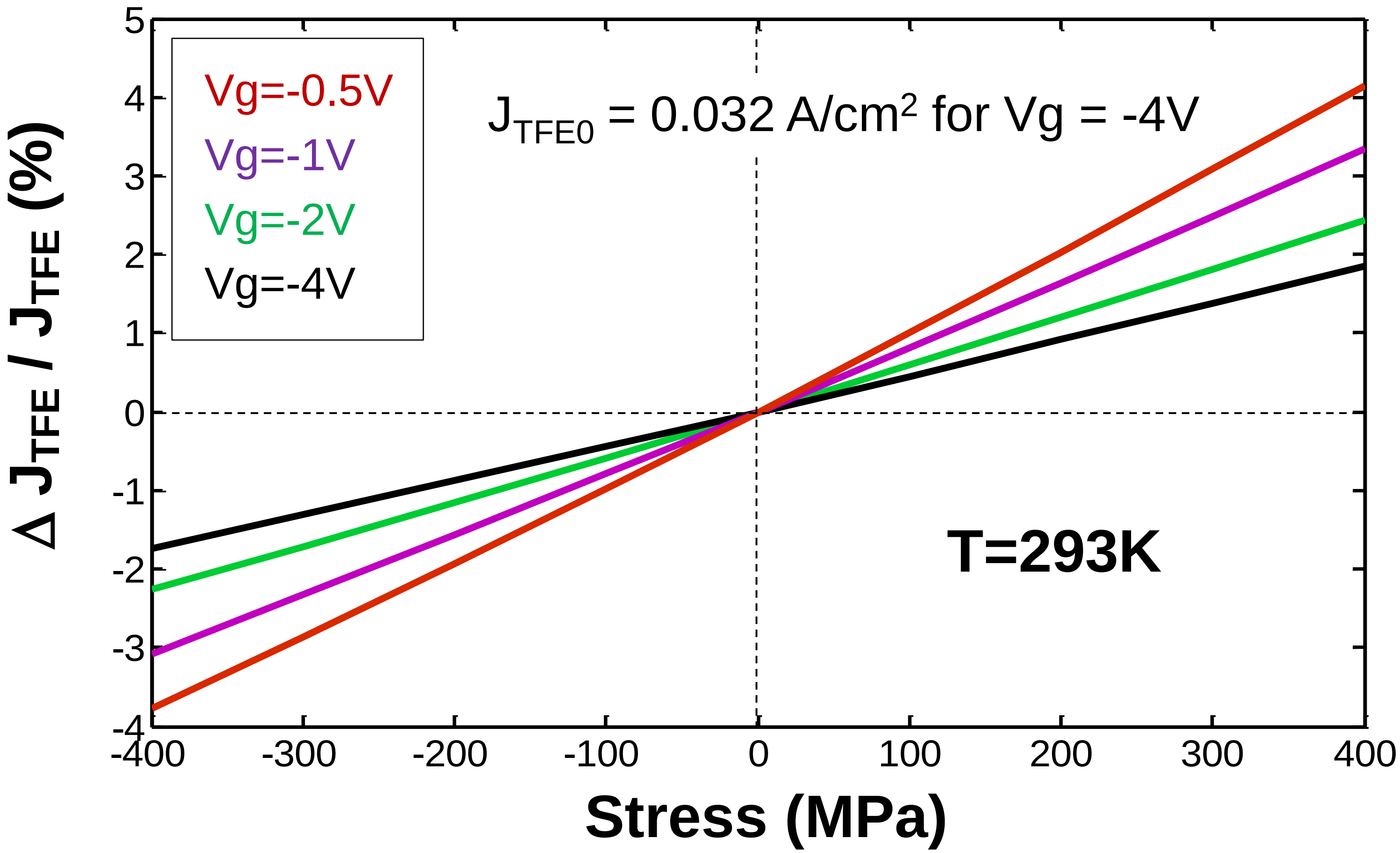
- sp^3d^5 tight-binding model
- Stress change both bond length and bond angle
- Reciprocal lattice also changes

Effect of Stress on FN Tunneling Current



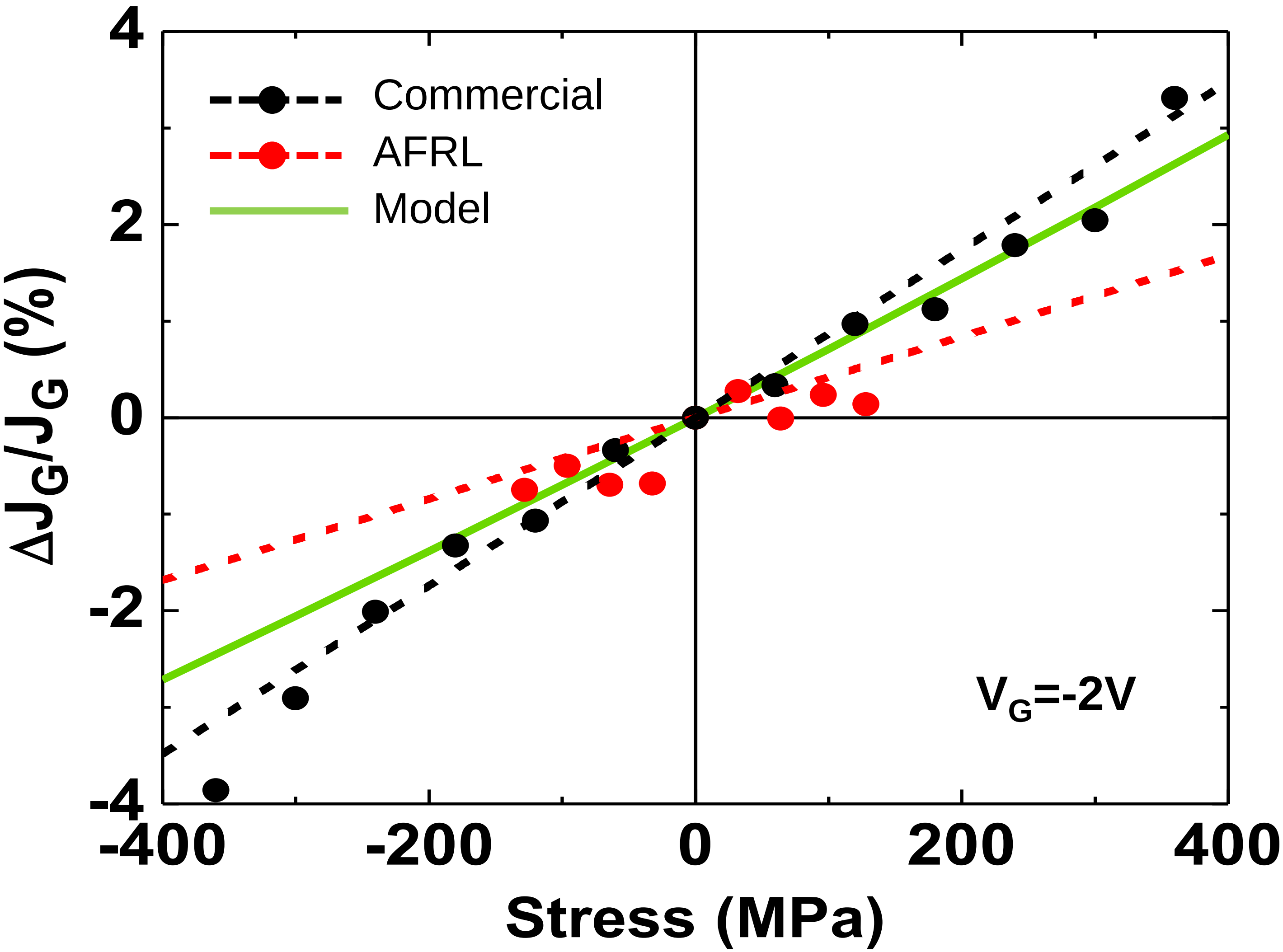
FN tunneling current increase (decrease) with tension (compression), <1.5% variation for 400MPa

Effect of Stress on TFE



Thermionic field emission increase (decrease) with tension (compression), <5% variation for 400MPa

Effect of Stress on Gate Leakage at Higher Bias



Summary of Stress Effect on Direct Tunneling

- At room temperature, FN tunneling and thermionic field emission are on the same order of magnitude.
- Both FN tunneling and thermionic field emission current increase/decrease under tensile/compressive stress.
- The stress-induced current change decreases with increasing gate bias $|V_G|$.

Outline

- Motivation
- Effect of Stress on GaN HEMT Channel Resistance
- Experiments on Stress Dependence of GaN HEMT Gate Leakage
- Theoretical Study of GaN HEMT Gate Leakage
- **Summary**
- **Path Forward**

Summary

- Gate current increases with tensile stress and decreases with compressive stress with varying sensitivity at specific biases
- At least two stress-dependent gate leakage mechanisms
  - Direct tunneling (FN and TFE) dominant at higher biases
    - Applicable for both HEMT processes (commercial, AFRL)
  - Trap-assisted tunneling at lower biases
    - Temperature dependent
    - Extracted trap energy ~0.31 eV
- Effect of stress on FN tunneling and TFE modeled in good agreement at higher biases where direct tunneling dominates

Path Forward

Yield strength: 15 GPa [1] → 0.2 GPa [2]

Temperature: 27 ºC → 1000 ºC

operating temperature
100 ºC to 400 ºC [3]

- Investigate stress dependence of gate leakage at higher stresses, biases, and substrate temperatures
- Investigate stress dependence of impact ionization and hot carrier injection
- Model trap-assisted tunneling current
- Investigate integration of stress models into reliability TCAD
- Investigate application of external bending stress on device failure measurements

Acknowledgments

MURI funding

Questions

Tight-binding Parameters

E(s,N)	-12.675
E(p,N)	1.519
E(s,Ga)	-2.090
E(p,Ga)	7.838
E(d,Ga)	-19.550

$\eta^{(1)}_{ss\sigma}$	-1.218
$\eta^{(1)}_{sap\sigma}$	-1.977
$\eta^{(1)}_{scp\sigma}$	1.626
$\eta^{(1)}_{pp\sigma}$	2.472
$\eta^{(1)}_{pp\pi}$	-0.648
$\eta^{(1)}_{sad\sigma}$	-0.400
$\eta^{(1)}_{pad\sigma}$	0.278
$\eta^{(1)}_{pad\pi}$	0.298

$\eta^{(2)}_{sas\sigma}$	0000
$\eta^{(2)}_{sap\sigma}$	0.011
$\eta^{(2)}_{pap\sigma}$	-0.110
$\eta^{(2)}_{pap\pi}$	0.000
$\eta^{(2)}_{scs\sigma}$	-0.100
$\eta^{(1)}_{scp\sigma}$	0.718
$\eta^{(2)}_{pcp\sigma}$	0.332
$\eta^{(2)}_{pcp\pi}$	-0.330

Tight-binding parameters. Onsite matrix E (eV) and coefficients $\eta = md^2V/\hbar^2$

[Ref. JJAP, vol.34, pp.5912]